

GÉOLOGIE de la *France*

2015 N° 1

SOMMAIRE

The Variscan belt: correlations and plate dynamics

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COUVERTURE/COVER



Landscape and blueschist rocks
on Île de Groix



Édité par le BRGM et la SGF

Géologie de la France est analysée dans la base des données PASCAL - GÉODE (BRGM/INIST).

FOREWORD

The venue of the Variscan 2015 conference at the University Rennes, and its theme, "correlations and plate dynamics", are the occasion to recall that, some 40 years ago, was convened in this university (25 September to 6 October 1974), under the aegis of CNRS and IGCP-UNESCO, an international meeting entitled: "La Chaîne varisque d'Europe moyenne et occidentale". Thanks to large-scale correlations, the purpose of this conference was namely to build a synthetic geodynamic reconstruction of the Variscan (or Hercynian) orogen. Although numerous recent studies emphasize the continuing advancement in the knowledge of the environment and processes that are at the origin of the Variscan belt, we are still trying today to reach a convincing and acceptable synthesis.

Let us remember that, in the 1970s, in spite of the ideas already established by Suess, Kossmat and Stille about the Variscan zonation in Central Europe, the first attempts of reconstructions using plate tectonics concepts were essentially performed on the Alpine belt. Both modern and traditional views on the Variscan belt were proposed at the 1974 meeting, where coexisted, on the one hand, plate tectonics reconstructions and, on the other, geosynclines. In the same time, geochronological data started to be easily available and thus contributed to better constrained models.

Among the main topics discussed were: i) the reworking of the Precambrian in the Variscan orogen because a better knowledge of the basement of the Paleozoic sediments prior to the Variscan tectonics was considered to be an absolute prerequisite to decipher the complexity of Variscan structures; ii) the eo-Variscan period, where the first geochronological data shed light on the importance of the magmatic events between 500 and 400 Ma, that were quite underestimated up to that moment. The first essays to apply plate tectonics models to the Devonian paleogeography led to different interpretations that questioned the place, the position and the direction of the subduction zones; iii) in the main Variscan regions, different reconstructions proposed to bridge the gap between the dismembered segments. A test was carried out on the Southern Variscan Branch using late Variscan strike slips postdating the opening of oceanic zones between continental blocks, and iv) the non European Paleozoic chains, Urals, Mauritanides and Appalachians, were also considered and correlations proposed.

Most of these issues are still topical at present, as exemplified by the contributions to the present conference. Concurrently, new concepts allow alternative views of the processes involved in building the orogen. As an example, the consideration of the Variscan orogen as an assemblage of successively accreted magmatic arcs rather than a collision of large continents allows to better explain some of the observed geological features. The concept of subduction rollback as an explanation of the juxtaposition of high-pressure rocks with migmatite complexes is another example. New geochronological methods help to better constrain the metamorphic and magmatic events and understand some existing data in a different way, etc. We could possibly regret the almost complete lack of contributions dealing with the sedimentary record of the Carboniferous-Permian times that could shed a different light on the understanding of the orogen. The involvement of this aspect into the research of the Variscan belt should in our opinion be particularly encouraged in the future.

The first day of the present meeting deals with the geology of some key regions of the orogen and examines how the gap between regional discrete information on dispersed fragments can be filled to arrive to a general seamless and coherent Variscan reconstruction from Morocco to the Bohemian Massif, passing through the Iberian peninsula, the Pyrenees, Corsica and Sardinia, the Alps, French Massif Central, Armorican Massif and other less studied regions like the Turkish Pontides.

The second day, more thematic, examines the history from the pre-Variscan heritage to the Variscan oceans and arcs, subduction environment and the related HP metamorphism, and processes underwent from the collision to the collapse of the orogen.

The morning of the third day is devoted to the granite magmatism, so characteristic of the Variscan orogen, and its relationship with ore genesis, an important topic if one keeps in mind that the Industrial revolution in the XIXth century was made possible thanks to the Variscan ores and carbon and that European economy could still draw some benefits from these resources.

Pavel Pitra and Philippe Rossi

Organizing committee

Pavel Pitra
Michel Ballèvre
José R. Martínez Catalán
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Scientific committee

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Vojtěch Janoušek
Jean Van Den Driessche
Philippe Rossi

FIELD TRIP GUIDE
(not available at the moment)

SCIENTIFIC PROGRAMME

9 – 11 June

Oral session – 9 June

8 h 45 – 9 h 00 Opening address

From the regional record towards the correlations from Iberia ... to the Bohemian Massif

9 h 00 – 9 h 15 **EGUILUZ L., SARRIONADÍA F., MARTÍNEZ-TORRES L.M., CARRACEDO M., GIL-IBARGUCHI J.I.:** Variscan evolution of the Ibero-Armorican Belt.

9 h 15 – 9 h 30 **AERDEN D., SAYAB M.:** Porphyroblast inclusion trail: the key to Variscan correlations between Iberia, Armorica and beyond.

9 h 30 – 9 h 45 **DIAS DA SILVA Í., GONZÁLEZ-CLAVIJO E., DÍEZ-MONTES A.:** Lateral escape tectonics in the Variscan Orogen: A new approach for the emplacement of the Allochthonous terranes and for the birth of the Central Iberian Orocline.

9 h 45 – 10 h 00 **MARTÍNEZ CATÁLAN J.R., GONZÁLEZ CLAVIJO E., MEIRELES C., DÍEZ FERNÁNDEZ R., BEVIS J.:** Detrital zircon U-Pb ages in Variscan syn-orogenic deposits of NW Iberia: Relationships between sedimentation and emplacement of the Allochthon.

10 h 00 – 10 h 15 **GÓMEZ-BARREIRO J., DURÁN OREJA M., MARTÍNEZ CATALÁN J.R., GONZALEZ CLAVIJO E., DIEZ MONTES A.:** The sole thrust of the Lower Allochthon to the west of the Morais Complex (Portugal): Correlation with the Lalín-Forcarei thrust in the Órdenes Complex (Spain).

10 h 15 – 10 h 30 **RUBIO PASCUAL F.J., MARTÍN PARRA L.-M., DÍEZ MONTES A., DÍEZ FERNÁNDEZ R., GALLASTEGUI G., VALVERDE VAQUERO P., RODRÍGUEZ FERNÁNDEZ L.R., HEREDIA N.:** Metamorphic records of partial subduction and continental collision in and around the parautochthon of the NW Iberian Massif.

10 h 30 – 11 h 00 *coffee*

11 h 00 – 11 h 15 **RIBEIRO M.A., AREIAS M., FERREIRA J., MARTINS H., SANT'OVAIA H.:** Geological and petrological constraints on the variscan evolution of the NW area of Port-Viseu Belt.

11 h 15 – 11 h 30 **PÉREZ-CÁCERES I., MARTÍNEZ POYATOS D.J., FERNANDO SIMANCAS J., AZOR A.:** Structural and geochronological advances in the Variscan evolution of SW Iberia

11 h 30 – 11 h 45 **COCHELIN B., CHARDON D., DENÈLE Y., GUMIAUX C., LE BAYON B.:** Variscan strain field and kinematics of the Pyrenees.

11 h 45 – 12 h 00 **LEMIRRE B., DE SAINT BLANQUAT M., DUCHÊNE S., POUJOL M.:** Signification of the late-Variscan high temperature event: a view from the Pyrenees.

12 h 00 – 12 h 15 **KRETSCHMER S., FRANKE W., WEMMER K., KÖNIGSHOF P., GERDES A.:** Tectono-metamorphic evolution of the Mouthoumet Massif (S-France): interference of orogenic accretion and anorogenic crustal extension.

12 h 15 – 12 h 30 **FAURE M., ROSSI P., LI X., FRÉVILLE K., MELLETON J., LIN W.:** Variscan orogeny in the Eastern Variscan Branch: New structural and geochronological insights from Corsica and surrounding areas.

12 h 30 – 14 h 00 *Lunch*

14 h 00 – 14 h 15 **FRÉVILLE K., FAURE M., TRAP P., MELLETON J., BLEIN O., LI X.:** Petro-structural evolution of the Belledonne massif: Implications for the Variscan orogenic evolution.

14 h 15 – 14 h 30	KUNZ B.-E., MANZOTTI P., VON NIEDERHÄUSERN B., BURN M., GIUNTOLI F., ENGI M.: Permian high-temperature metamorphism in continental units of the Western Alps (Italy).
14 h 30 – 14 h 45	OKAY A.I., TOPUZ G.: Variscan orogeny in the Pontides, northern Turkey.
14 h 45 – 15 h 00	ARETZ M., HERBIG H.-G.: The palaeogeographical position of the Eastern Moroccan Meseta in Mississippian times: new data and model from the Jerada Massif (NE Morocco).
15 h 00 – 15 h 15	WERNERT P., ŠTÍPSKÁ P., CHOPIN F., SCHULMANN K., BOSCH D., BRUGUIER O., EL HOUICHA M., CORSINI M., GHIEFFE J.-F.: Tectonometamorphic evolution of the intracontinental orogeny exemplified by the Rehamna massif (Morocco, Variscan belt).
15 h 15 – 15 h 30	PEŘESTÝ V., LEXA O., JEŘÁBEK P.: The effect of rheology on the strain partitioning in the crustal section at the western margin of the Teplá-Barrandian Unit.
15 h 30 – 16 h 00	<i>Coffee</i>
16 h 00 – 16 h 15	FRIEDEL C.-H., HUCKRIEDE H., LEISS B., ZWEIG M.: Sedimentary vs. tectonic mélanges - a case study from the Harz Mountains (eastern Rhenohercynian Belt).
16 h 15 – 16 h 30	RAHIMI G., MASSONNE H.-J.: Petrology and age-dating of a Variscan garnet-bearing micaschist from the northern Fichtelgebirge, Germany.
16 h 30 – 16 h 45	BAPTISTE J., MARTELET G., FAURE M., BECCALETTO L., PERRIN J.: Up-to-date regional gravity and aeromagnetic data to unravel the geological patterns of the pre-Mesozoic substratum of the Paris Basin.
16 h 45 – 17 h 00	EDEL J.-B., SCHULMANN K.: Paleomagnetic constraints on the evolution of the Variscan belt in Carboniferous-Permian times.
17 h 00 – 17 h 30	BALLÈVRE M.: How fresh-water bivalves record the growth and collapse of the Variscan belt.

10 June

From pre-Variscan heritage to Variscan oceans & arcs

- 8 h 45 – 9 h 00 **LINNEMANN U.:** The Cadomian orogen: constraints of timing, orogenic zoning, and crustal growth based on U-Pb and Hf isotopes of detrital and magmatic zircon.
- 9 h 00 – 9 h 15 **EGUILUZ L., MARTÍNEZ-TORRES L.M., SARRIONADÍA F., CARRACEDO M., GIL-IBARGUCHI J.I.:** The Ibero-Armorican Belt: an evolving island-arc along northern Gondwana between ca. 650 and 480 Ma.
- 9 h 15 – 9 h 30 **DE POULPIQUET J.:** Is the magnetic Ibero-Armorican arc the trace of a Cambro-Ordovician aborted rift ?
- 9 h 30 – 9 h 45 **CHELLE-MICHOUE C., LAURENT O., MOYEN J.-F., BLOCK S., GARDIEN V., PAQUETTE J.-L., COUZINIE S.:** New U-Pb and Hf zircon data from the eastern Massif Central: From Gondwana to Pangea in a nutshell.
- 9 h 45 – 10 h 00 **MOYEN J.-F., COUZINIE S., MINTRONE M., VANDERHAEGHE O., CHELLE-MICHOUE C., LAURENT O., BLOCK S., GARDIEN V., PAQUETTE J.-L., ZEH A., POIJOL M.:** Rifting the Gondwana: record of an ultra-thinned continental margin in the French Massif Central.
- 10 h 00 – 10 h 15 **AERTGEERTS G., LORAND J.-P., MONNIER C., LAHONDÈRE D., LA C.:** New petrological constraints on amphibolites and serpentinised peridotites from the variscan Champtoceaux Complex, southern Armorican Massif, France.
- 10 h 15 – 10 h 45 *Coffee*
- 10 h 45 – 11 h 15 **DEWEY J.:** Ophiolite Enigma resolved ?
- 11 h 15 – 11 h 30 **FRANKE W.:** Variscan oceans: how many, where and when ?
- 11 h 30 – 11 h 45 **GUTIÉRREZ-ALONSO G., FERNÁNDEZ-SUÁREZ J., HENDERSON B., PASTOR-GALÁN D., LÓPEZ CARMONA A., MURPHY J.-B., WEIL A.B., PEREIRA M.F., FERNÁNDEZ-LOZANO J.:** Another model for the Western Europe Paleozoic Variscan evolution: questioning redundant subduction and oceans.
- 11 h 45 – 12 h 00 **ZURBRIGGEN R.:** Metagreywacke gneiss terranes rich in peraluminous granitoids -indications for a unique type of early Paleozoic orogeny.
- 12 h 00 – 12 h 30 **LABROUSSE L., DURETZ T., GANZHORN A.-C., GERYA T.:** Partial melting and continental subduction: coupling metamorphic reactions and collisional dynamics.
- 12 h 30 – 14 h 00 *Lunch*

Subduction & HP metamorphism

- 14 h 00 – 14 h 30 **WARREN C., MOTTRAM C.-M., MCDONALD C.-S., REGIS D.:** Progress and pitfalls in linking age to stage in metamorphic rocks.
- 14 h 30 – 14 h 45 **LOTOUT C., PITRA P., POIJOL M., RUFFET G., TONDELLA E., VAN DEN DRIESCHE J.:** Variscan subduction of an Ordovician granite : the Lévézou Massif, French Massif Central.
- 14 h 45 – 15 h 00 **LI B., MASSONNE H.-J.:** P-T evolution of Variscan high-pressure rocks from the Northern Malpica-Tuy shear zone in NW Spain.

- 15 h 00 – 15 h 15 **LÓPEZ-CARMONA A., ABATI J., PITRA P., LEE J.-K.-W., GUTIÉRREZ-ALONSO G., FERNÁNDEZ-SUÁREZ J.:** High-pressure rocks in the Variscan belt of Western Europe: the Malpica-Tui Complex (NW Iberian Massif).
- 15 h 15 – 15 h 30 **THIÉRY V., ROLIN P., DUBOIS M., GONCALVES P.:** New UHP evidences from the inner part of the Variscan belt: geology of the Chavanon sequence, French Massif Central.
- 15 h 30 – 16 h 00 *Coffee*

From collision to collapse of the orogen

- 16 h 00 – 16 h 15 **REGORDA A., MAROTTA A.-M., RODA M., LARDEAUX J.-M., SPALLA M.-I.:** Effects of mantle hydration and viscous heating on the dynamics of mantle wedge in a subduction system: differences and similarities of 2D model predictions with examples from the Variscan crust.
- 16 h 15 – 16 h 30 **MAIEROVÁ P., SCHULMANN K., GUILLOT S., LEXA O., ŠTÍPSKÁ P., ČADEK O., JANOUŠEK V.:** Linking PT evolutions of Bohemian Massif and Tibetan granulites through numerical modelling: insight to geodynamics of internal orogens.
- 16 h 30 – 17 h 00 **HASALOVA P.:** Pervasive melt flow in the continental crust: examples from Variscan Orogeny.
- 17 h 00 – 17 h 15 **CRUCIANI G., FRANCESCHELLI M.:** Amphibole-bearing migmatite from NE Sardinia (Italy) and its constraints on Variscan partial melting.
- 17 h 15 – 17 h 30 **TEYSSIER C., WHITNEY D.L., ROGER F., REY P., TRAP P.:** Coeval eclogitization and migmatization during orogenic collapse (Montagne Noire dome).

11 June

Granite magmatism & ore genesis

8 h 45 – 9 h 15	CASTRO A., PEREIRA F., FERNÁNDEZ C., JANOUSEK V.: Granite magmatism of the European Variscan belt. An overview.
9 h 15 – 9 h 30	BROSKA I., PETRÍK I., BEZÁK V.: Genesis and tectonic evolution of the West-Carpathian Variscan granites.
9 h 30 – 9 h 45	COUZINIE S., LAURENT O., MOYEN J.-F., ZEH A., VEZINET A., VILLAROS A.: Mg-K magmatic suites as a tool to scan the composition of the Variscan orogenic mantle, case studies from the French Massif Central.
9 h 45 – 10 h 00	LAURENT O., COUZINIÉ S., VANDERHAEGHE O., ZEH A., MOYEN J.-F., VILLAROS A., GARDIEN V.: U-Pb dating of Variscan igneous rocks from the eastern French Massif Central: southward migration of coeval crust- and mantle- melting witnesses late-orogenic slab retreat.
10 h 00 – 10 h 15	KRONER U., ROMER R.-L., HALLAS P., STEPHAN T.: Extrusion tectonics from an intracontinental subduction zone: The late orogenic granites of the Saxo-Thuringian Zone.
10 h 15 – 10 h 45	<i>Coffee</i>
10 h 45 – 11 h 00	STEPHAN T., HALLAS P., KRONER U., BUSKE S.: Crustal-scale 3D modelling of the Allochthonous Domain of the Saxo-Thuringian Zone: constraints from high-resolution 2D seismic profiles.
11 h 00 – 11 h 15	TOPUZ G.: Early to Late Carboniferous granite and gabbro intrusions in the eastern Pontides and its relations with the Variscan Orogeny in the Central Europe.
11 h 15 – 11 h 30	MELLETON J., GLOAGUEN E.: Timing of rare-elements (Li-Be-Ta-Sn-Nb) magmatism in the European Variscan belt.
11 h 30 – 12h 00	GLOAGUEN E.: Ore deposits around the Ibero-Armorican arc and their relations to the Variscan orogeny.
12 h 00 – 12 h 30	<i>Concluding discussion</i>
12 h 30 – 14 h 00	<i>Lunch</i>

POSTER SESSION – 9-11 June

AGUILAR C., MONTERRAT L., RECHE J., ŠTÍPSKÁ P., SCHULMANN K., MUÑOZ J.A., CASAS J.M., POWELL R.: Open-system processes during decompression: An example from contact aureole migmatites from the Roc de Frausa Massif (Eastern Pyrenees).

AVIGAD D., ROSSI P., GERDES A.: Origin of "Pan-African" micaschist from Variscan Corsica: detrital zircon U-Pb-Hf constrains on provenance and Cadomian paleogeography.

BALLOUARD C., POUJOL M., JOLIVET M., DUBOIS C., HALLOT E., BOULVAIS P., TARTÈSE R., DABARD M.-P., RUFFET G.: Geochronological and thermochronological constraints on the Carboniferous magmatism of the Armorican Massif: from the source to the exhumation.

BOUENITELA V., BALLÈVRE M.: Migmatite xenoliths and garnet xenocrysts in the Pouldu microgranitic dykes: (Southern Armorican Domain, western France): a window into the lower crust.

CALASSOU T., ZÁVADA P., SCHULMANN K., HASALOVÁ P., ŠTÍPSKÁ P.: Microstructural and anisotropy of magnetic susceptibility records of a granite intrusion in Bohemian massif (Central Sudettes, Variscan orogenic belt).

CASINI L., MAINO M., CUCCURU S., FUNEDDA A., OGGIANO G., PUCCINI A., ROSSI P.: Early Permian necking of the Corsica-Sardinia massif.

CHARDON D., ROQUES., ARETZ M.: Kinematic reappraisal of nappe tectonics and late orogenic sedimentation in the Southern French Massif Central.

COKE C., DIAS R., AMARAL F., ROMÃO J., RIBEIRO A.: Cambro-Ordovician unconformities in the Central Iberian zone: extensional or compressional process ?

DIAS R., MOREIRA N., RIBEIRO A.: Dextral strike-slip tectonics in Iberia and the Pangeia Assemblage: evidences of the Tardi-Variscan Deformation event in South Portuguese Zone.

DIAS R., RIBEIRO A., COKE C., MOREIRA N., ROMÃO J.: Central Iberian Arc : just a model ?

DUCHÊNE S., SAMALENS N., SEVERAC J.-L., DRIOUCH Y., NTARMOUCHANT A., DAHIRE M.: A window to the crust below Moroccan Massif Central: high temperature crustal xenoliths trapped in Permian lavas.

SEGHIR E.M., EL OUARDI H., LINDHORST J., CHAPONNIERE P., KAMBUROV D.: The structural control of the tin mineralisation at the Bou El Jaj project (NE of the central Hercynian massive).

FRANCESCHELLI M., MARCELLO F., CRUCIANI G., MONTOMOLI C., CAROSI R., PUXEDDU M.: A review of Variscan metamorphism and deformation in northern Sardinia, Italy.

FRIEDEL C.-H.: Geothermobarometry of very low-grade Devonian metabasalts of the Elbingerode Complex (Harz Mountains, Germany) - implications of chlorite and phengite composition.

GALY C., VANDERHAEGHE O.: When a partially molten orthogneiss meets a syntectonic granite along the Northern flank of the Canigou massif, Axial Zone of the Pyrenees.

JANAK M.: Variscan metamorphic evolution of the Western Carpathians: Tatric and Veporic units.

KARAOUI B., EL OUARDI H., MAHMOUDI A.: Evidence of E-W dextral shear zones in the Bas Draâ inlier (Western Anti Atlas, Morocco): Macro - to microtectonic arguments and geodynamic implications.

LOM N., CAN ÜLGEN S., ÖZGÜL N., SUNAL G., İŞSEVEN T., NATAL'IN B.A., CELÂL ŞENGÖR A.M.C.: The eastern extent of the Hercynian orogenic belt: The history of the Istanbul Zone before and during the assembly of the Pangaea.

LÓPEZ-CARMONA A., RUBIO PASCUAL F.J., ARENAS R.: P-T constraints in the internal domains of the Variscan Orogen through pseudosection modelling: the Barrovian section of Somosierra (Central Iberian Massif).

- MANZOTTI P., BALLÈVRE M., POUJOL M.:** Detrital zircon geochronology in blueschist facies meta-conglomerates from the Western Alps: implications for the late Carboniferous to early Permian palaeotopography.
- MOREIRA N., PEDRO J.C., ROMÃO J., DIAS R., ARAÚJO A., RIBEIRO A.:** The Neoproterozoic-Cambrian transition in Abrantes Region (Central Portugal): Lithostratigraphic correlation with Cambrian Series of Ossa-Morena Zone.
- NARDIN E., CHARDON D., ARETZ M., BERGER J., POUJOL M.:** Ordovician reorganization of the European Gondwana: Towards an integrated magmatic - sedimentary - structural scheme across the Variscan domain.
- PEREIRA I., DIAS R., BENTO DOS SANTOS T., MATA J.:** Figueira de Castelo Rodrigo – Lumbrals Anatectic Complex (Iberia): the role of shearing on exhuming high grade rocks.
- POCHON A., GAPAIS D., GUMIAUX C., BRANQUET Y., GLOAGUEN E., CAGNARD F., MARTELET G.:** Geographical and lithological relationships between high-density magnetic lithologies and Variscan Sb ± Au mineralizations in the Armorican belt (France).
- ROMER R.-R., KRONER U.:** Chemical character of Variscan granites of the Saxo-Thuringian Zone.
- SIMAN P., HIRATA T.:** I - Type tonalite Evolution: new isotopic and geochronological ICP-MS/TIMS data interpretation from the Central Western Carpathians, Slovakia.
- SOARES A., DIAS R.:** Fry and RF/Φ strain methods constraints and fold transection mechanisms; an example of progressive deformation in the Iberian Variscides.
- STREMTAN C.C., RYAN J.G., SAVOV I.:** Mantle-crust interaction recorded in the latest Variscan plutons of the Romanian Southern Carpathians.
- THIÉBLEMONT D.:** High-Sr - Low-Yb (“adakitic”) Namuro-Westphalian peraluminous granites from South-Brittany: evidence for high-pressure crustal melting at the “collapse stage” of the Variscan orogen.
- TRAP P., CENKI-TOK B., ROGER F., RABIN M., FRÉVILLE K., CARRY N., PAQUETTE J.-L.:** Strain partitioning during migmatitic dome formation in the Variscan Montagne Noire massif (Southern French Massif Central).
- WAFIK A., TRAORE K., NZAOU MABIKA N., SAQUAQUE A.:** Contribution to the geological and metallogeny study of Bakoudou Golden Ore Deposit (Gabon).
- ZÁVADA P., JEŘÁBEK P., HASALOVÁ P., RACEK M., KONOPÁSEK J., LEXA O.:** Extrusion of anatectic lower crust from orogenic infrastructure: an example from the Eger crystalline unit (Bohemian Massif, Czech Republic).
- ZUCALI M., SPALLA I., RODA M., ZANONI D.:** Pre-Alpine contrasting tectono-metamorphic evolution within the Southern Steep Belt (Central Alps).

ABSTRACTS

Porphyroblast inclusion trail: the key to Variscan correlations between Iberia, Armorica and beyond

AERDEN Domingo¹
SAYAB Muhammad²

During most of the 20th century, interpretations of inclusion trails were dominated by the idea that porphyroblasts rotate whenever the matrix around them is sheared. This model implied that (1) porphyroblast rotation axes should lie normal to the stretching lineations in sheared rocks, and (2) that subsequent folding or shearing in another directions should significantly disperse these axes. However, 3D microstructural analysis has shown both predictions to be false in numerous orogens where inclusion-trail axes are commonly parallel to both stretching lineations and fold axes, and have remarkably consistent orientations despite later folding and shearing. The reason is that curved inclusion trails generally form by overgrowth of one or multiple crenulations without (much) porphyroblast rotation, and consequently preserve the original orientation of included fabrics. This provides a powerful methodology for resolving and correlating deformation histories based on regional-scale "mapping" of inclusion trail orientations. We applied this methodology to 3 groups of oriented samples from the Armorican Massif, amongst which 10 samples of garnet-glaucophane schist from Ile de Groix, 4 samples of plagioclase schist from the South Brittany coast (schistes de Pouldu), and 2 samples of Ky-And-St schist from the North Armorican Zone. The strike of inclusion trails in these samples were measured in horizontal thin sections, and for a few samples, also the trend of included foliation-intersection-axes (FIA) were determined using radial sets of vertical thin sections. The combined data exhibit a high degree of consistency with 3 trend-maxima standing out (see Figure). Significantly, inclusion trails associated with each trend exhibit consistent relative timing relationships

that establish the following trend sequence: WNW-ESE, NNW-SSE, NE-SW. Relative timing criteria include (1) truncation relationships between foliations preserved in porphyroblast cores versus rims, (2) compositional differences between garnets (e.g. Mn content) including differently trending foliations in the same samples, and (3) field evidence, such as the overprinting of a N140 trending glaucophane lineation (correlated with our earliest inclusion trails) by a younger NNW-SSE trending crenulations and folds on Ile de Groix (Philippon *et al.*, 2009). The 3 inclusion-trail trends in Brittany are inferred to reflect 3 periods characterized by different bulk crustal shortening directions normal to these trends.

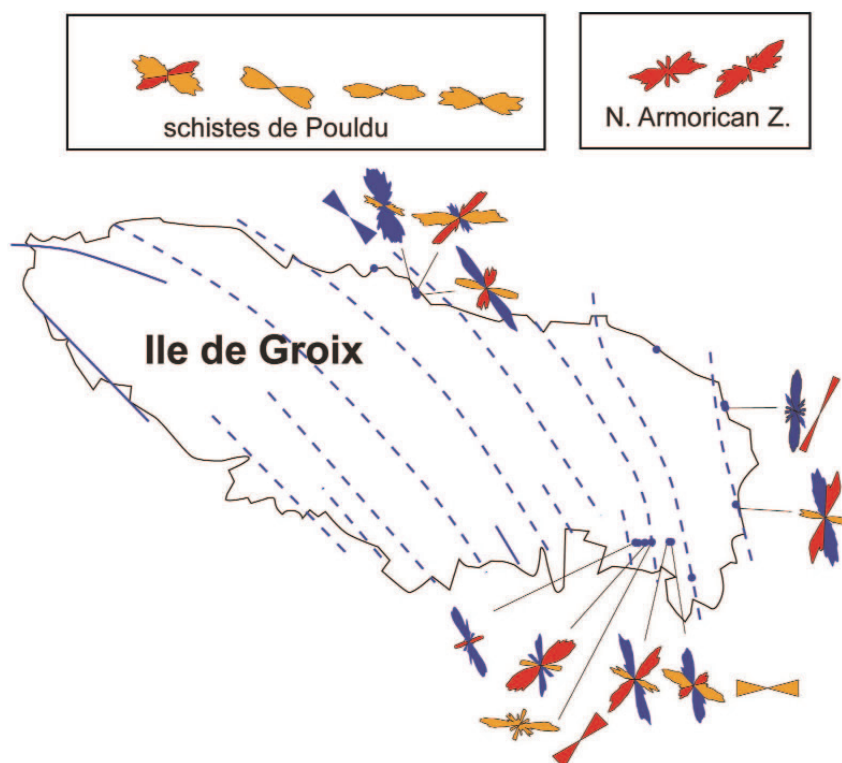
Interestingly, a very similar sequence of inclusion-trail trends was reported by Aerden (2004) in NW-Iberia, but appears about 20° rotated anticlockwise with respect to the new data from Armorica. We contend that this angular difference reflects the upper-Cretaceous rotation of Iberia that accompanied the opening of the Atlantic Ocean. The amount of rotation is somewhat less as what paleomagnetic data has previously suggested, possibly reflecting heterogeneous rotations between different portions of Iberia caused by Alpine intraplate deformation.

References

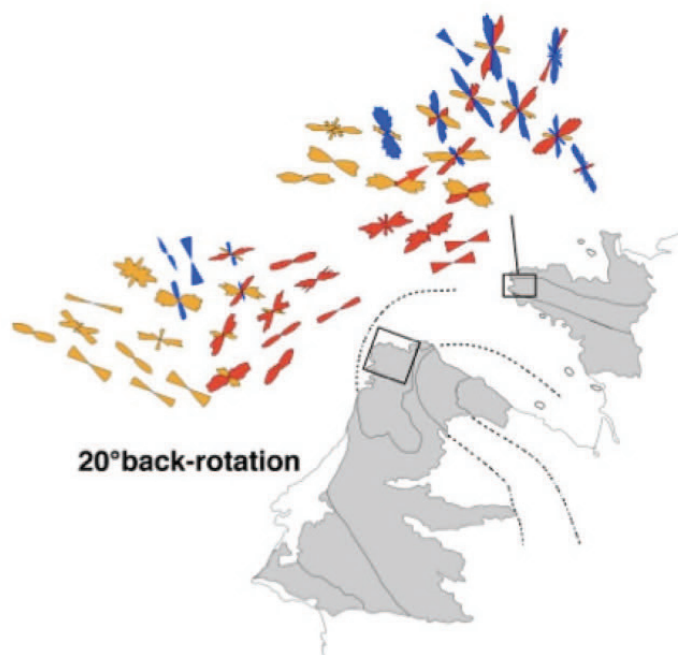
- Aerden D.-G.-A.-M. (2004) - Correlating deformations in the Iberian Massif (Variscan belt) using porphyroblasts; implications for the development of the Ibero-Armorican Arc. *Journal of Structural Geology*, 26, 177-196.
- Philippon M., Brun J.-P., Gueydan F. (2009) - Kinematic records of subduction and exhumation in the Ile de Groix blueschists (Hercynian belt, Western France). *J. Struct. Geol.* 31, 1308-1321.

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Overview of inclusion trail strikes plotted in moving average rose diagrams and FIA trends (bow-tie symbols) from Ile de Groix and mainland Brittany (boxes). The trend sequence is WNW-ESE (yellow), NNW-SSE (blue), NE-SW (red). Stipple lines mark the orientation of the main stretching lineation.



Comparison with data from NW Iberia after 20° back-rotation

New petrological constraints on amphibolites and serpentinitised peridotites from the variscan Champtoceaux Complex, southern Armorican Massif, France

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The Champtoceaux Complex (CC) crops out in the south-western part of the Armorican Massif. It is composed of three allochthonous units, sometimes eclogite-bearing, thrust onto an autochthonous metapelitic unit during the variscan orogeny. The strongly dismembered intermediate unit (Drain Formation - DF, Folie Siffait Formation - FSF, le Havre Formation - LHF and Pont de Barel Formation - PBF) is composed of amphibolites and strongly serpentinitised peridotites and is commonly considered to mark the south-armoric eo-variscan suture of the variscan orogeny. In this study, we provide new petrological and bulk-rock geochemical data that provide new constraints on these mafic-ultramafic rocks.

The FSF and DF amphibolites display amphibolite facies assemblages (magnesio-hornblende, garnet), whereas the PBF and LHF amphibolites show typical greenschist facies mineralogical assemblage (actinolite-albite). All the associated peridotites are strongly serpentinitised (more than 90%) and record a low temperature lizardite event (<320 °C). A second stage of serpentinitisation has been identified in the LHF peridotites. Lizardite was replaced by antigorite during a higher temperature event (320 < T < 460 °C). Peridotites from the FSF contains relics of olivine (Mg # = 0.89), never found in the other peridotites of the CC. PBF spinel lherzolites display rather fertile major element compositions (Al₂O₃: 2.43-2.71 wt%; CaO: 1.54-1.98 wt%) whereas DF spinel lherzolites have more residual composition (Al₂O₃: 1.18 wt% and CaO: 0.17 wt%). Both show undepleted HREE flat patterns (HREE > 1.4 x CI-chondrites). Major and trace element

abundances coupled with spinel compositions (Cr #: 0.09 to 0.14) suggest low degrees of partial melting (<5 %) for PBF lherzolites. FSF harzburgites show more residual major (Al₂O₃ < 2.0 wt%; CaO < 0.32 wt%) and trace element compositions (HREE < 1 x CI-chondrites) indicating higher degree of partial melting (5-10 %). LHF harzburgites-dunites have strongly residual major and trace element compositions (Al₂O₃ < 0.65 wt%; CaO < 0.1 wt%; HREE < 0.2 x CI-chondrites) which suggest the highest degree of partial melting for CC peridotites (20-25 %) in agreement with their spinel composition (Cr#: 0.43 to 0.45). All CC peridotites show variably LREE-enriched patterns indicative of melt-rock reaction/metasomatic processes.

Mafic rocks have basaltic composition with SiO₂ ranging from 44.7 to 51.3 wt% and Na₂O + K₂O ranging from 1.84 to 5.54 wt%. PBF and DF amphibolites show slightly depleted to enriched LREE-patterns; LHF amphibolites display flat REE pattern and FSF amphibolites exhibit LREE-depleted pattern. All mafic rocks but the FSF amphibolites show negative Nb-Ta anomaly suggesting a subduction component. These new petrological data suggest two geological settings for the mafic-ultramafic rocks from the Champtoceaux Complex. The PBF, DF and LHF mafic rocks show geochemical features of an arc/back-arc supra-subduction related setting whereas the FSF amphibolites show compositions more consistent with a MORB-like oceanic environment. Our interpretation is supported by most of the compositional features of the associated mantle-derived rocks.

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Open-system processes during decompression: An example from contact aureole migmatites from the Roc de Frausa Massif (Eastern Pyrenees)

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The Roc de Frausa Massif is a dome structure formed by the interference of Variscan and Alpine folds. The structure is outlined by an Upper Proterozoic–Lower Cambrian metasedimentary sequence separated into three units by two Pre-Variscan orthogneiss sheets and intruded by two Variscan igneous bodies: a tonalite-granite composite pluton on the upper levels and mafic rocks on the intermediate crustal levels. The Variscan antiformal structure resulted from the combination of the buoyancy-driven (diapiric) uprise of high-grade rocks accompanying the intrusion of mafic rocks with lateral compression (D2; Fig. 1b), which overprinted a horizontal flow fabric (D1; Fig. 1a). Granulite facies migmatites with distinct mineral assemblages and chemical compositions were preserved in the gabbro-diorite contact aureole. Patch, stromatic and schollen migmatites are recognized in the inner contact aureole, while schollen migmatites and residuum melanosomes are found as xenoliths inside the gabbro-diorite. The seven-phase assemblage quartz-garnet-biotite-sillimanite-cordierite \pm K-feldspar-plagioclase is

present in patch and schollen migmatites, whereas stromatic migmatites and residuum melanosomes contain a sub-assemblage lacking sillimanite and K-feldspar, and locally quartz. In spite of the different mineral assemblages, the four types of migmatites register similar *P-T* retrograde histories. These *P-T* paths provide peak metamorphic conditions \sim 7–8 kbar and 840 °C followed by nearly isothermal decompression to 5 kbar and isobaric cooling to 690 °C the approximate solidus temperature (Fig. 1c).

The preservation of the different types of migmatites can be explained by open-system processes that took place during decompression and cooling (Fig. 2). These processes involve repeated cycles of H₂O-fluxed melting accompanied by melt loss. The fluids released by the crystallizing gabbro-diorite, would have infiltrated the metasediments and enhanced melting. Release of fluids and melt loss were probably favoured by coeval D2 lateral compression. Furthermore, the high temperature of the rocks would have favoured the Variscan doming and the related antiformal structure.

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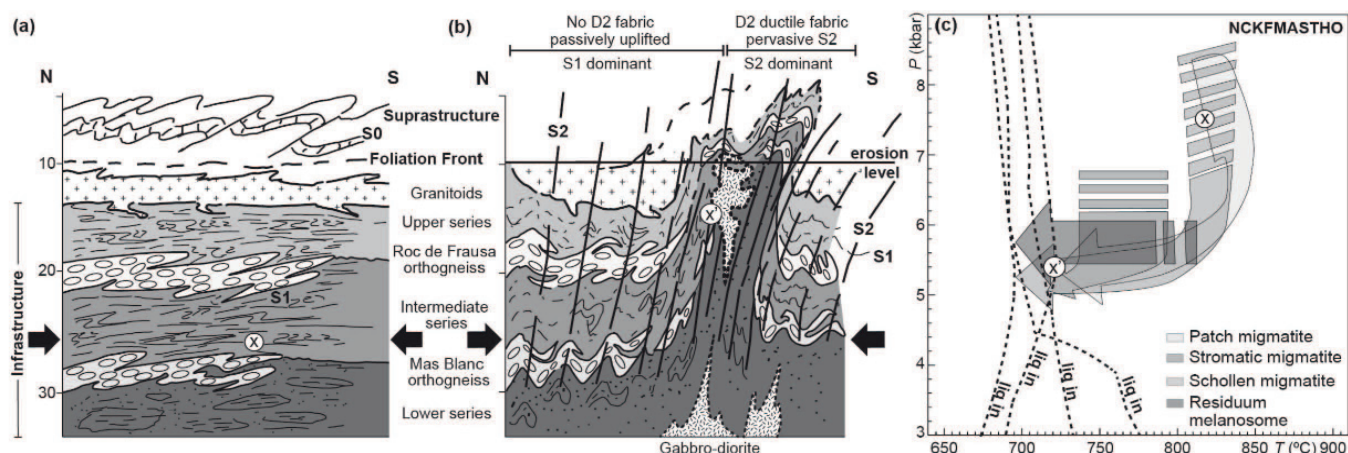


Fig. 1.- Geodynamic model for the tectonic evolution of the last stages of the Variscan orogeny in the Roc de Frausa Massif: (a) D1 deformation and the calc-alkaline intrusion took place during the compressive phase at 320–311 Ma, (b) Mafic intrusive bodies and D2 deformation event occurred during tectonic exhumation at ca. 307 Ma, (c) Summary of P–T paths for four types of migmatites from the Intermediate series affected by the gabbro–diorite contact aureole. Idealized position of the studied samples is indicated by symbols including reference $X \rightarrow X'$. For clarity only the solidus of the pseudosections for the different samples is included and underlined by a dashed line.

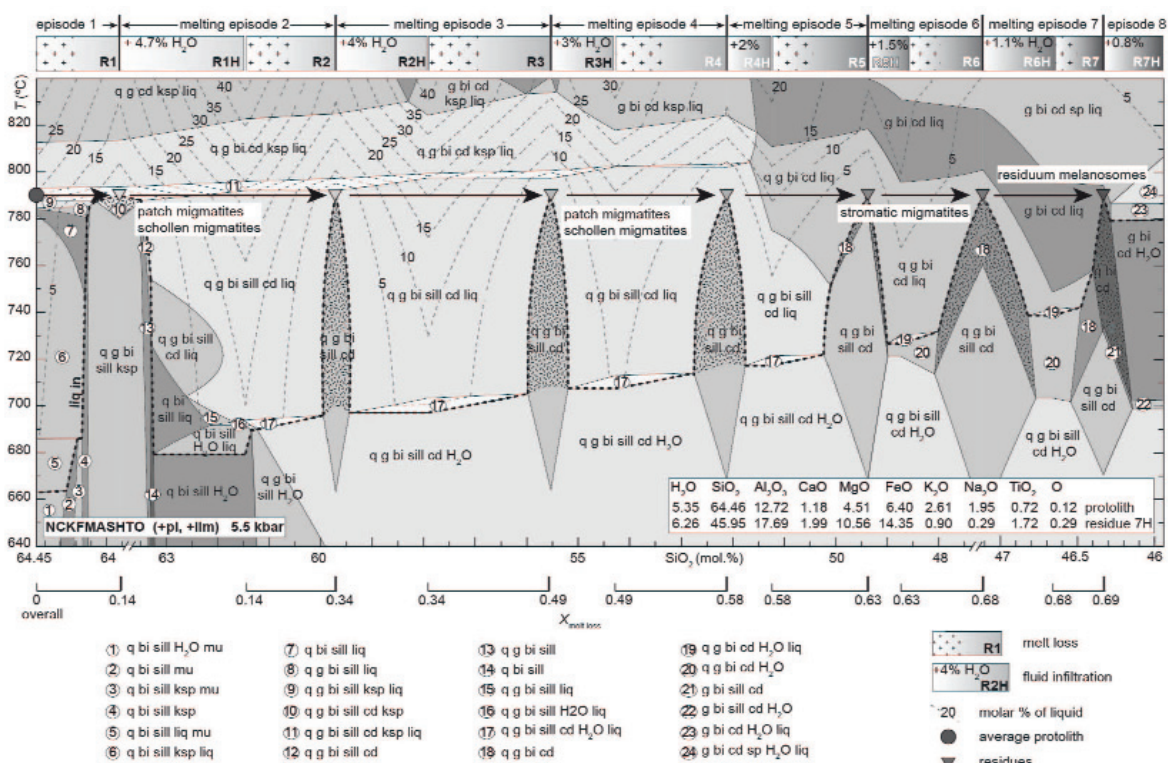


Fig. 2.- Calculated T–X_{melt loss} pseudosection (+pl, +ilm) at 5.5 kbar constructed for an opensystem model showing multiple partial melt-loss–fluid infiltration events that took place during the gabbro–diorite intrusion in the adjacent rocks from the Intermediate series. X_{melt loss} is the proportion of melt removed from the protolith composition at 790 °C in mol.%. Stippled fields indicate the partial preservation of granulite facies assemblages. The solidus is underlined by a dark thick-dashed line.

The palaeogeographical position of the Eastern Moroccan Meseta in Mississippian times: new data and model from the Jerada Massif (NE Morocco)

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The today's juxtaposition of the classical European (Iberian) Variscan units and those of North African, which resulted from the Cainozoic geodynamic evolution of the western Mediterranean, makes the question for the Carboniferous palaeogeographical patterns particularly interesting.

The Jerada Massif is part of the Palaeozoic basement of the Eastern Moroccan Meseta, which is today widely covered by Mesozoic–Cainozoic strata. The Eastern Moroccan Meseta belongs to the internal zone of the North African Variscides and it is characterized by a poorly dated Late Devonian–Tournaisian "Eovariscan" synmetamorphic folding event. Palaeozoic outcrops are restricted to several isolated massifs. The Jerada Massif is a W-E orientated internally folded and faulted synclinorium (max. 15 km wide) situated about 60 km south of Oujda. It contains the stratigraphically most complete Carboniferous succession of the Eastern Moroccan Meseta. Hence, the Mississippian succession is important for reconstructions of basin evolution, geodynamic setting and palaeogeographical relations of that segment of the Moroccan Variscides. The succession is composed of a Tournaisian(?)–Visean basin fill sequence unconformably overlain by a Namurian to Westphalian paralic sequence. It ends with coal-bearing strata of Westphalian B–C age below the Variscan unconformity.

After extrusion of rhyolitic, rhyodacitic, dacitic and andesitic volcanics at deep-seated faults, first basin plain sediments (bedded cherts and intercalated pyroclastics) and then toe-of-slope and lower slope sediments level out the volcanic submarine relief. The second phase is documented in a variegated succession of interbedded shales, siltstones, calcareous greywackes, calciturbidites and polymictic

conglomerates. This mostly distal gravitative resedimentation pattern is accentuated on the southern limb of the synclinorium by meter- to hectometer sized limestone olistolites, among those the remains of microbial-sponge buildups, which document the collapse of a southern carbonate platform. On top of slope sediments (shales with few sandstone intercalations) a shallow, mixed carbonate–siliciclastic platform developed. Now the siliciclastic influx is from northern directions, indicating the creation of a relief in the north. The latest Visean is characterised by a basin emergence. During Visean times, the polarity of the basin remains stable. Deepening is towards the northeast, where the most distal deposits (almost exclusively fine-grained siliciclastic rocks) are found.

The geodynamic relations between Western and Eastern Moroccan Meseta are controversial, like the general palaeogeographical setting. For Jerada, we suggested a back arc basin dissected by strike-slip faults due to oblique, south-directed subduction further north. The repeatedly suggested eastern prolongation of the Eastern Moroccan Meseta into the internal Betico-Rifean zones and the Kabylies can be rejected based on new biofacies data (calcareous algae, rugose corals, ammonoids) for the Jerada Massif. These data show that a supposed Palaeotethyan affinity does not exist. The taxa have strong affinities to the contemporaneous NW European fauna and flora, which is also found in similar datasets for the Western Moroccan Meseta and to a minor extent the Anti-Atlas. Thus the Eastern Moroccan Meseta should be clearly separated from southern European Variscides like the Malaguides and the Montagne Noire. In Morocco, only the Palaeozoic basement of the Rif shows strong affinities to this tectonic realm, at least in Mississippian times.

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Origin of "Pan-African" micaschist from Variscan Corsica: detrital zircon U-Pb-Hf constrains on provenance and Cadomian paleogeography

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Northern Corsica exposes a succession of Neoproterozoic "Pan-African" micaschists underneath a non-metamorphosed Paleozoic sediments. The "Pan-African" micaschists, related to Armorica, crop out in the areas of Galeria and the Agriate desert. Except from rare occurrences of mafic bodies, intrusive rocks including granites are absent. LA-ICP-MS U-Pb-Hf analyses of detrital zircons from micaschists of SW Agriate allowed to better constrain the origin of the metasediments and their age of deposition, as well as to bridge the gap with other Cadomian units in peri-Gondwana terranes.

The U-Pb analyses revealed that a preponderance of the zircons yielded Neoproterozoic ages concentrating between 0.72-0.53 Ga with major peaks at 0.59 Ga and 0.65 Ga. A few zircons yielded Grenvillian (0.9-1.1 Ga) as well as older Mesoproterozoic ages (1.3-1.6 Ga), and a number of detrital zircons yielded 2.2-1.9 Ga (Paleoproterozoic, Eburnian). The oldest zircons detected are 2.7 and 2.9 Ga. The youngest detrital zircons are Late Ediacaran to Early Cambrian (0.53 Ga) setting the maximum age of deposition of the "Pan-African" schists in Corsica. The overall detrital zircon signal resembles that of other Late Neoproterozoic sedimentary successions in Western Europe suggesting that the Corsican succession was deposited in a proto-Cadomian basin.

Although a number of Neoproterozoic-aged zircons yielded positive ϵ_{Hf} values, many of the Neoproterozoic zircons yielded negative ϵ_{Hf} and Meso- to Paleoproterozoic TDM(Hf) ages. The vertical spread of ϵ_{Hf} values of the Neoproterozoic zircons indicates mixing of old crust with juvenile magmas supporting the provenance involved Pan-African to Cadomian igneous activity in an Andean-type environment. While this is a-priori consistent with derivation from Pan-African terranes of north Africa, the fact that the

major peak in the detrital zircon ages is at 590 Ma (and that a considerable proportion of the detrital zircons yielded younger ages peaking at 557 Ma), indicates significant input from Cadomian arcs that resided within or at the vicinity of the proto-Cadomian basin in which the "Pan-African" micaschist of Corsica was deposited.

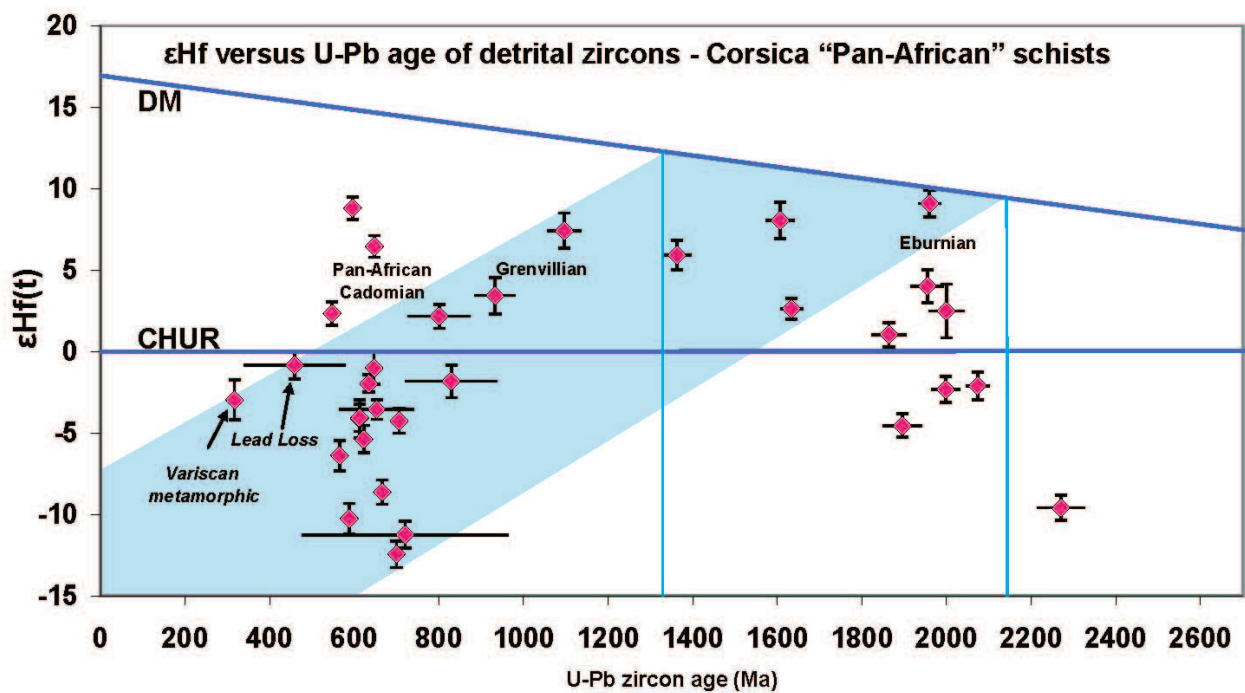
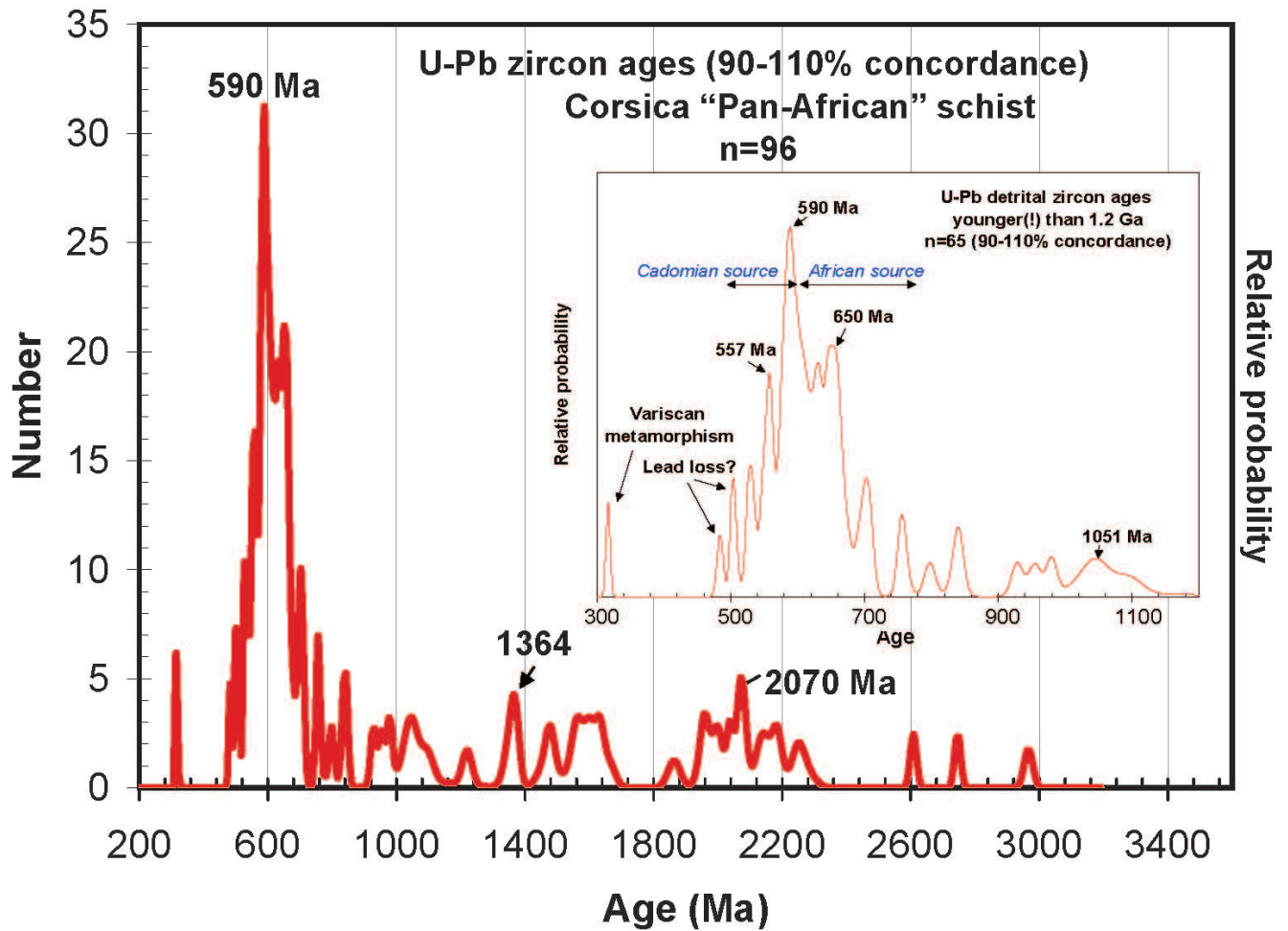
The presence of Eburnean-aged detrital zircons (especially those with positive ϵ_{Hf} values) may indicate the Corsica basin fringed the West Africa Craton (WAC). However, pre-Variscan restoration of "Pan-African" Corsica places it more than 1 000 km north of their present position (Rossi *et al.*, 2009) and it is doubted if WAC-derived sediments traveled such a long distance. Likewise, the northern part of the WAC was fringed by a late Pan-African mobile belt and it is not clear if detritals were capable of crossing it. The northern part of the WAC may have been therefore sealed and cut off from the fluvial system by the time the Corsica micaschists were deposited. The presence of Mesoproterozoic-aged zircons is also inconsistent with derivation from the WAC because rocks of this age are not known there (e.g. Abati *et al.*, 2012). Thus, Pre-Neoproterozoic zircons may have simply sourced from WAC-like and other crustal vestiges (including Mesoproterozoic) that were possibly entrained within the Cadomian realm itself.

As a whole, the "Pan-African" micaschists of Corsica resemble other metasedimentary successions of Cadomian western Europe in that they were deposited during the Late Ediacaran-Cambrian, in a broad peripheral back-arc basin that fringed north Gondwana. They were fed by detritus derived from Neoproterozoic "Pan-African" orogens but contribution from Cadomian arcs is also inferred.

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How fresh-water bivalves record the growth and collapse of the Variscan belt

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Palaeozoic non-marine bivalves belong to three extinct families, namely the Archanodontidae, Myalinidae and Anthracosiidae, whose systematic affinities are still discussed. The non-marine bivalves are found in deltaic, fluvial and lacustrine sediments throughout the Variscan belt (from Portugal to Poland) and its foreland. Their spatial and temporal distribution has been reconstructed based on an extensive search in the literature, initially fuelled by some field observations.

During the Devonian and the Carboniferous, the large-shelled Archanodontidae are restricted to the southern margin of the Laurussia supercontinent, where they successfully colonize brackish- to fresh-water ponds and channels within the estuaries and the deltas. During the Early Carboniferous (Tournaisian and Visean), Myalinidae and Anthracosiidae are found in a few places, then they invade all foreland basins during the Serpukhovian, Bashkirian and Moscovian (Namurian and Westphalian). In these basins, non-marine bivalves have been used for zonal purposes. Few of them are found in the intramontane basins during the Moscovian (late Westphalian). By contrast, almost all Kasimovian-Gzhelian (Stephanian)

basins have their bivalve communities. These become rarer during the Permian.

To explain these changing patterns through time, we will first examine some biological aspects of the life cycle of the non-marine bivalves (taking into account the potential caveats of an actualistic approach), then discuss their link to the tectonic history of the Variscan belt. The main phase of growth of the Variscan belt occurred at the same time than the foreland basins were subsiding due to flexural loading. In these areas, eustatic sea-level fluctuations created large-scale but short-lived biotopes that were convenient for opportunistic species such as the non-marine bivalves. The mountain belt was drained by a few major rivers, some of them being colonized by the non-marine bivalves. Later on, the collapse of the Variscan belt was associated to a dynamic change of the drainage patterns inside the belt, allowing transient connections between lakes and rivers. Drying up of the climate by the Permian resulted in a severe reduction of the diversity of the non-marine bivalves, few of them surviving the end-Permian crisis.

Geochronological and thermochronological constraints on the Carboniferous magmatism of the Armorican Massif: from the source to the exhumation

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During the Carboniferous, the Armorican Massif experienced an intense magmatism resulting in the emplacement of numerous granitic intrusions of various types (Capdevila, 2010; Fig. 1). In southern Brittany, most of these intrusions are syntectonic peraluminous leucogranites and can be associated with significant U mineralization. To the north, most intrusions are U barren granites with more variable compositions such as the composite intrusion of Ploumanac'h. Vigneresse *et al.* (1989) proposed that some of these granites belong to the "so-called" High Heat Production Belt (HHPB, Fig. 1), and represent melting of a Proterozoic to Paleozoic U-rich metasedimentary lower crust. However, the source, the U-enrichment processes as well as the intrusion ages and the exhumation history of most of those granites are still poorly known.

To the south, petrological, geochemical and geochronological studies (Tartèse and Boulvais, 2010; Tartèse *et al.*, 2011a, b; Ballouard *et al.*, 2015) as well as apatite fission track dating (AFT) (this work) were performed on the Lizio, Questembert and Guérande leucogranites (Fig. 1) to constrain their magmatic and exhumation history:

- (1) Nd and Sr isotope data suggest that they result from partial melting of metasedimentary formations. The southward increase of the ϵ_{Nd} and ISr could be explained by sedimentary sources being gradually dominated by Paleozoic sediments relative to Brioverian sediments (Fig. 2).
- (2) Along the South Armorican Shear Zone, the Lizio and Questembert granites emplaced at ca. 316 Ma (zircon U-Pb) while, to the south, the Guérande granite emplaced at ca. 310 Ma (zircon and monazite U-Th-

Pb; Fig. 3).

- (3) AFT dating revealed that the three leucogranites were exhumed to the near surface during the Middle Jurassic (AFT central ages range from 195 to 155 Ma; Fig. 3).

To the north, petro-geochemical data from the Ploumanac'h composite intrusion revealed that mantle and metasedimentary sources were successively involved. The oldest unit (Bt-Hbl granite) was emplaced at 308.8 ± 2.5 Ma while the youngest unit (Bt-Ms leucogranite) was emplaced at 301.3 ± 1.7 Ma (zircon U-Pb). This intrusion was exhumed during the Triassic (AFT central age of 207 ± 9 Ma; Fig. 3).

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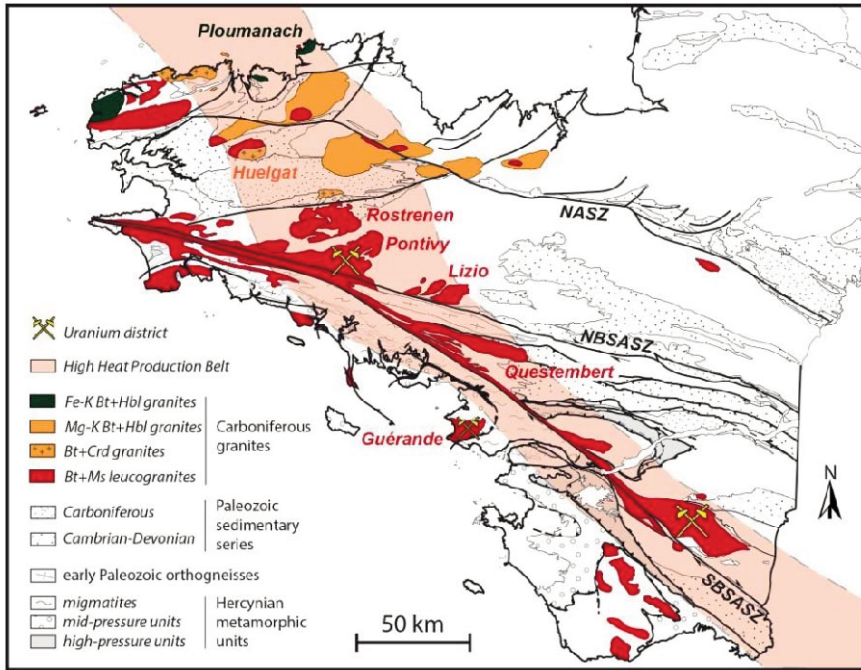


Fig. 1.- Geological map of the Armorican Massif localizing the four types of carboniferous granites (Capdevila, 2010). The map is modified from Gumiaux, 2003. NASZ: North Armoric Shear Zone; NBSASZ: Northern Branch of the South Armoric Shear Zone; SBSASZ: Southern Branch of the South Armoric Shear Zone.

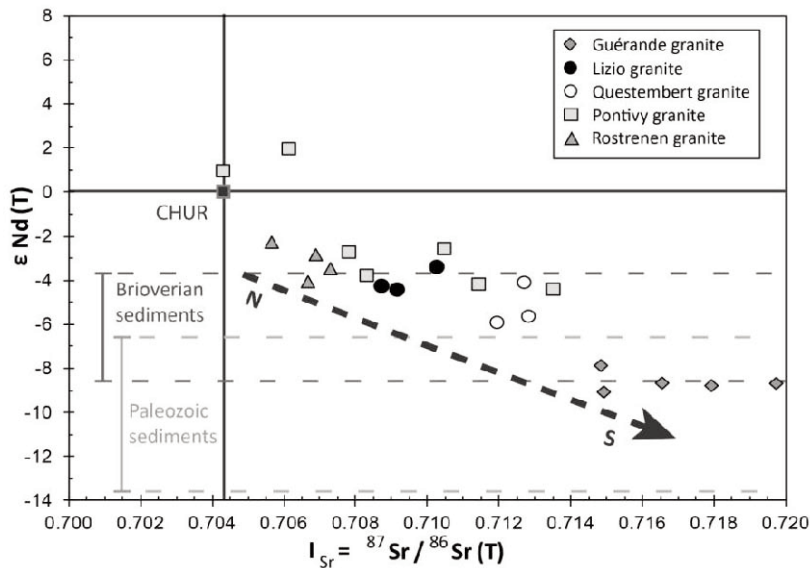


Fig. 2.- Sr and Nd isotope compositions of some peraluminous granites from the Armorican Massif. ϵNd and I_{Sr} are calculated for an age of 310 Ma. The vertical bars represents $\epsilon Nd(T)$ composition of the Brioverian and Paleozoic sediments from Central Brittany. From Ballouard et al., 2015.

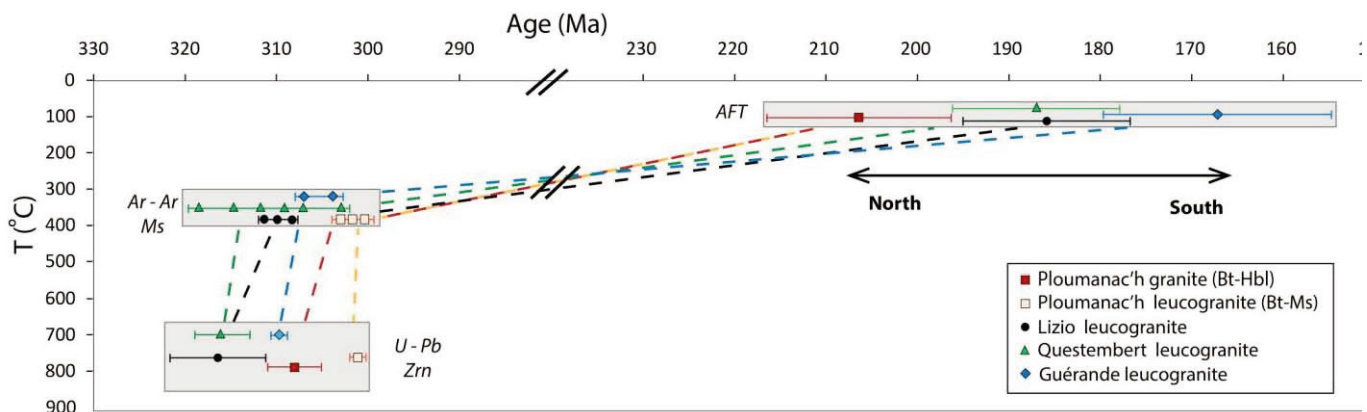


Fig. 3.- Simplified thermal history of the Guérande, Questembert, Lizio and Ploumanac'h granites. Grey boxes represent the uncertainty on the emplacement temperature of the granites, the uncertainty on the closure temperatures of the geochronometers (U-Pb Zrn and Ar-Ar Ms) and the partial annealing zone of apatite fission tracks (AFT). Ar-Ar Ms ages from the Ploumanac'h granites are unpublished.

Up-to-date regional gravity and aeromagnetic data to unravel the geological patterns of the pre-Mesozoic substratum of the Paris Basin

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The Paris Basin is an intracratonic basin made of Meso-Cenozoic sediments unconformably overlying the Variscan substratum. The Pre Mesozoic substratum of the Paris Basin constitutes an important segment of the Variscan belt in Western Europe. It crops out around the Paris Basin in four massifs, namely the Massif Armoricaire, Massif Central, Vosges, and Ardennes, in the West, South, East, and Northeast of the basin, respectively. Although these massifs are rather geologically wellcharacterized, their lithological and structural extensions below the Paris Basin are poorly known. Consequently, the structural relationships, and the geological framework of this hidden part of the Variscan belt are still in debate.

Compilation, processing, and interpretation of new high resolution aeromagnetic surveys combined with up-to-date gravity data covering a large southern half of the Paris Basin provide an unprecedented insight into the buried pre Mesozoic substratum. Our geophysical interpretations support that the pre-Mesozoic substratum is separated into two western and eastern structural domains, by the N-S striking Paris Basin Magnetic Anomaly (PBMA; Fig. 1).

The general interpretative sketch is provided in Figure 1. Among the noticeable features we propose a new extension of the Saxo-Thuringian and Armorican domains in the eastern part of the Paris Basin, north of the Vosges.

These domains are separated by a N150-160° discontinuity located in the central part of the Paris Basin near and superimposed on the PBMA, and in the northeast by the NE-SW Bray-Vittel dextral fault.

West of the PBMA, regional N150-160E aeromagnetic and gravity discontinuities gradually straiten the Central Armorican and Ligerian domains towards the highly deformed area of Montmarault, at the junction between the PBMA and Sillon Houiller fault. In the western part of the Paris Basin, the Nort-sur-Erdre fault, well acknowledged as the eo-Variscan suture, extends eastwards up to the PBMA. The strike of the North Armorican shear zone changes eastwards from E-W to NW-SE, as it is gradually offset by regional N160E striking dextral faults.

In addition to the structural information, correlation between the geophysical maps and the geology of the Massif Armoricaire reveals lithological extensions in the Paris Basin substratum : for instance, outstanding geophysical signatures define (i) the late Cadomian post-orogenic plutons, (ii) the Cambro-Ordovician magmatism, in the northeast (Normandy) and in the southeast (Choletais), respectively. Also, due to its Fe rich content, the early Ordovician Armorican sandstone formation is well depicted by aeromagnetic anomalies.

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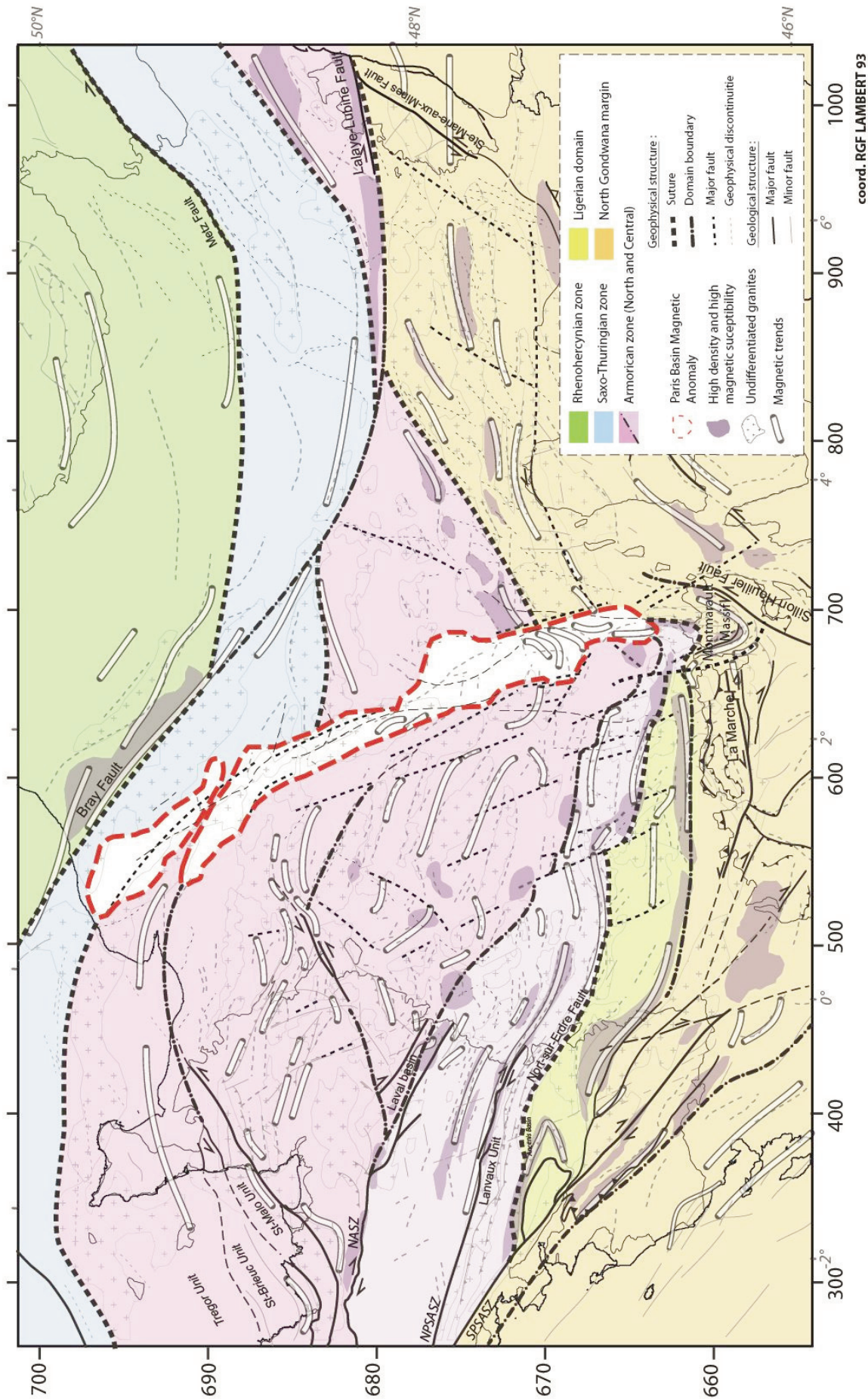


Fig. 1.- Tectonic map of the Pre-Mesozoic substratum of the Paris Basin obtained by (re)processing of aeromagnetic and gravimetric anomalies, and correlation with geological structures recognized in the surrounding Variscan massifs. NASZ: North American shear zone; NBSASZ: North Branch of the South American Shear Zone; SBSASZ: South Branch of the South American Shear Zone. PBMA: Paris Basin magnetic anomaly.

Migmatite xenoliths and garnet xenocrysts in the Pouldu microgranitic dykes (Southern Armorican Domain, western France): a window into the lower crust

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The South-Armorican Domain (SAD) consists of (i) medium- to high-grade partially melted gneissic rocks, (ii) low-grade greenschist- to blueschist facies micaschists and metabasites (Ile de Groix, le Pouldu) and (iii) various types of granitic intrusions (Guidel, Ploemeur). Geological mapping and structural analysis have shown that the partially melted rocks are separated from the overlying low-grade schists by a ductile extensional shear zone (Gapais *et al.*, 1993; Brown and Dallmeyer, 1996; Turrillot *et al.*, 2009).

In the western part of the SAD, between Lorient and Concarneau, the low-grade Pouldu micaschists are intruded by NS-trending microgranitic dykes (Cogné, 1960, Jégouzo and Ballèvre, 2011). The microgranitic dykes cut across the ductile structures developed during the early stages of the Variscan history. The N-S trend of the microgranitic dykes is regionally consistent with an E-W stretching during the late stages of the Variscan history (see also Turrillot *et al.*, 2011). One of the dykes displays a large amount of xenoliths and xenocrysts:

- the enclosing Pouldu Formation is made of (i) felsic orthogneisses, locally displaying K-feldspar porphyroclasts ("porphyroid"), (ii) albite-bearing amphibolites deriving from variably altered mafic volcanics, (iii) a large amount of albite-bearing micaschists (metagreywackes) and (iv) a few metapelites. The latter contain garnet + chloritoid (with ilmenite and minor rutile inclusions) assemblages, with retrograde chlorite;
- the microgranite consists of (i) abundant phenocrysts of idioblastic biotite, quartz, plagioclase and K-feldspar, (ii) a groundmass made of the same minerals as the phenocrysts. The margin of the dyke is finer-grained compared to the core, with an abundant development of granophyric intergrowths;
- two types of xenoliths are found in the microgranite. A few of them are observed along the external part of the dyke, and are similar to the enclosing micaschists. However, most of them display a typical gneissic appearance, with

alternating layers made of quartz-feldspar and biotite-sillimanite \pm garnet. Biotite ($X_{Mg} = 0.46-0.49$) and garnet ($Alm_{80}Sps_{02}Prp_{15}Grs_{03}$) have been used to calculate an equilibrium temperature of about 750 °C. Spinel grains (never in contact with quartz) occur as unoriented aggregates in the sillimanite - biotite matrix, associated with very fine grained muscovite;

- the garnet xenocrysts ($Alm_{78}Sps_{02}Prp_{15}Grs_{05}$) have sometimes aligned ilmenite inclusions (indicating growth during deformation) and show a reaction rim made of muscovite (replacing cordierite?) and biotite.

The garnet xenocrysts and the gneissic xenoliths are interpreted as deriving from the source of the partial melts, and entrained during magma ascent in the dyke. The gneissic xenoliths are similar to the Port Navalo gneisses (e.g. Jones and Brown, 1990), outcropping 25 km further east. A similar kind of gneissic basement is therefore assumed to be present in the deeper part of the crust below the Pouldu Formation.

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Genesis and tectonic evolution of the West-Carpathian Variscan granites

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The West-Carpathian granitoids represent mostly part of the Variscan crystalline complex which forms core mountains within midcrustal nappes. The Variscan metamorphosed granitic rocks of the Western Carpathians (orthogneisses) formed during the Cambrian and Ordovician, are represented by I-type diorites (500–450 Ma, Veporic unit, Putiš *et al.*, 2001, 2008) and S-type granites (470 Ma, Nízke Tatry Mts., Petrík *et al.*, 2006) originally derived from the Gondwana realm. The West-Carpathian granitoids belong to the oldest Variscan granitoids in the Europe. They are represented by I-type tonalites and granodiorites (360–365 Ma) and with associated slightly younger S-type, two mica granites and granodiorites (340–350 Ma). A typical feature of the earliest I-type magmatism is magma mixing between granitic and dioritic magmas producing relatively basic tonalites with enclaves. The I-type granite massifs of the Western Carpathians most probably originated in an arc-related environment south of the Massif Central (Ligerian) within the Galatian superterrane, an assemblage of Gondwana derived fragments. The high age of I-type magmatism in the Western Carpathians marks the beginning of a north-dipping subduction of the Paleotethys ocean. We suggest a term “Proto-Tatric” for that part of the Galatian superterrane, where Devonian/Mississippian I-type granitoids were emplaced, now incorporated into Alpine Tatric and Veporic nappe system within the West-Carpathian mountain chain. The presented model suggests that after dextral shear to the west following the oblique collision of the superterrane (Galatian), the Proto-Tatric terrane started drifting eastwards after the initiation of Permian sinistral shear. Later, the Permian shear zones have been reactivated during the Paleo-Alpine collision,

which also contributed to the eastward drift of the Proto-Tatricum. Finally, the crystalline cores of the Carpathian arc were extruded to the east to their present position on the southern rim of the European platform during the Neo-Alpine (Neogene) orogen.

The Variscan orogen was terminated by Permian magmatism producing A-type granites and specialised F-B-Sn-Li S-type granites. The A-type granites (260 Ma) formed bodies along long strike slip lineaments. The A-type granites show a rift-related origin and are considered as anorogenic granites originated in within-plate conditions. On the other hand the Permian specialised S-type granites from the Gemeric unit originated after the main collision of Variscan orogeny. In this term they could be classified as post-collisional granites emplaced during the peak of crustal thickening in similar way as Himalaya tourmaline bearing Manaslu granite above the Main Central Thrust. Both the A-type granite magma in the Veporic unit and specialised boron rich S-type granite magma in the Gemeric unit were strongly influenced by depolymerizing effect of F responsible for their special mineralogy (Sn-Nb-Ta-W-Mo minerals).

The variability of Variscan granites observed in the Western Carpathians contributes to the understanding of global Variscan tectonics by pointing to the upper Devonian subduction earlier than the main Variscan granite-forming event at 330 Ma.

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Microstructural and anisotropy of magnetic susceptibility records of a granite intrusion in Bohemian massif (Central Sudettes, Variscan orogenic belt)

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In the Bílá voda valley, in western Sudetes, several magmatic bodies elongated in NE-SW direction intruded the strongly folded Sněžník Metamorphic Unit. The major perspective of our study is to understand the emplacement conditions and fabric development in these sheet-like bodies of granite during progressive transposition of the metasedimentary host rocks from S1 fabrics shallowly dipping to the SE to subvertical NE-SW trending S2 fabrics. In the host rock lithologies around the major map-scale granite bodies, numerous small sills of granite up to 1 m thick show open to isoclinal folds concordant with the S1 fabric of the host rock metasediments. Locally, granite sheets crosscut the host rock fabric at low angles to the S2 axial fold cleavage. Succession of deformation events and rheological properties of the granites will be addressed by

means of microstructural analysis of deformation mechanisms for quartz and feldspar (bulging, subgrain rotation and grain boundary migration) in different parts of the largest granite sill. The AMS (Anisotropy of Magnetic susceptibility) record throughout the major sill and several small scale granite sheets will be critically analyzed for superposition of different deformation events (e.g. corresponding to S1 and S2 in the host rocks) and later subsolidus overprint. Preliminary results suggest that the magmatic and submagmatic fabrics are present only in the middle part of the pluton. In addition, the CPO (crystal preferred orientation) of quartz will be analyzed to constrain in the major granite body the temperature gradient and the deformation gradient respectively increasing and decreasing from the edges to the center of this body.

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Early Permian necking of the Corsica-Sardinia massif

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The Corsica-Sardinia Batholith is a late Variscan composite magmatic province formed episodically during the Carboniferous-Permian transition. The evolution of the batholith reflects two main growth stages. The early plutons have a dominant crustal component (ASI 1.02/1.18, $\epsilon\text{Nd}_{300\text{Ma}}$ -2.8/-8.7) and are mostly associated to conjugate E-W to NW-SE shear zones that collectively form a huge N-S granitic ribbon. The AMS signal and the emplacement fabric of plutons indicate a mean extension direction about N100-140°. This pre-Permian massif is segmented into several crustal-scale boudins bridged by earliest Permian (290 - 275 Ma) plutonic-volcanic complexes derived from hybrid (crust/mantle) magmas, as suggested by field evidence and by geochemical and isotopic data (ASI 0.44/1.17, $\epsilon\text{Nd}_{285\text{Ma}}$ -4.1/+6.3). Permian massifs emplaced within NE-SW to NNE-SSW dilatational jogs and step-over

developed along brittle-ductile shear zones consistent with N20-40° extension. The apparent rotation of the regional σ_3 axis at about the Carboniferous-Permian transition is consistent with CW 90° rotation of the Maures-Estérel Corsica-Sardinia (MECS) block (Edel *et al.*, 2014), stretching of an heterogeneous crust and necking of pre-Permian batholith in response to northeastward displacement of Laurussia relative to stable Gondwana and intraplate shearing of Pangaea.

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Granite magmatism of the European Variscan belt. An overview

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Granite (*sensu lato*) magmatism is the most relevant feature of the European Variscan belt (EVB). Geochronologic data have revealed that magmatic activity lasted for long time periods along the Lower and Upper Paleozoic to Permian. Peaks of maximum magmatic activity are identified at the Upper Cambrian-Lower Ordovician and Carboniferous-Permian. According to petrological constraints, often ignored in tectonic models, both intracrustal and lithospheric processes are the responsible for granite magma generation in varied styles of time-changing tectonic environments. Granites are useful to constrain ages in orogenic belts. Some of these granites and associated gabbroic rocks are unequivocally related to lithosphere subduction involving a metasomatized mantle and sublithospheric silicic subducted sources. Others are clearly derived from crustal recycling. Thus, the meaning of ages in terms of geodynamic processes is considered according to petrogenesis and emplacement of granite magmas.

In a broad sense, the entire belt can be considered as an amalgamation of microcontinents and magmatic arcs,

starting with a Neoproterozoic tectonic activity, continuing with processes of rifting, subduction, crustal recycling and granite magma generation at different stages along the Paleozoic, and ending finally with the generation of large granite-granodiorite batholiths at the Upper Carboniferous-Permian times. All these features confer to EVB the category of an accretionary belt. Some of the batholiths of the EVB are formed by peraluminous anatectic granites derived from Neoproterozoic and Paleozoic metasedimentary sources. However, the large volume of granite magmatism is formed by calc-alkaline batholiths (I-type) that underwent extensive contamination with local peraluminous metasediments. The origin of these large batholiths remains controversial in the EVB. Current models are unable to explain the geochemical features in terms of source composition. However, important advances have been made along the last years on the petrogenesis and tectonic implications of large calc-alkaline batholiths. These new advances constitute a new paradigm that must be considered in the context of the EVB.

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Kinematic reappraisal of nappe tectonics and late orogenic sedimentation in the Southern French Massif Central

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The Montagne Noire Massif (Southern France; Figure 1) exposes the transition between the hinterland of the Variscan orogen and the Carboniferous flysch basin enclosed in the Ibero-armoric syntax. The massif consists of Palaeozoic sediments wrapping a Late- to post-orogenic gneiss dome occupying a releasing bend of the Cévennes fault. Nappes from the southern flank of the dome are considered to have emplaced during flysch sedimentation by south-vergent thrusting on the basis of stratification/cleavage relationships and southward facing of some of the large-scale recumbent folds. However, no stratigraphic data supports a northern origin for the nappes and the largest olistoliths in the flysch (the Ecailles de Cabrières; Figure 2) show affinities with series of the Mouthoumet massif located further South. Here we reevaluate the structure, kinematics and deformation/sedimentation relationships of the lower part of the nappe pile, with an emphasis on the flysch sediments.

The lower nappe pile, instead of being made of two nappes (the right side up Faugères nappe and the “overlying” Mont Peyroux overturned nappe; Arthaud, 1970) is interpreted as a coherent unit taken into a recumbent syncline (F1) with a N-S axis, refolded by map-scale ENE upright folds (F2) (Figures 1 & 2). The unit is overlain by the overturned Pardailhan unit to the West and the pic de Vissou unit to the East. The wildflysch, which contains olistoliths of late Viséan to Serpukhovian (at least Namurian “A”) ages, is restricted to the normal limb of the F1 fold and is bounded to the North and floored by the ENE-striking, S-dipping Roquessels fault. All rock types of the unit except the wildflysch display a single ENE-trending and shallowly plunging stretching lineation carried by a regional

schistosity being affected by the map scale, ENE-trending F2 folds.

The main deformation episode is characterized by pervasive top-to-the ENE shearing combined with vertical shortening throughout the substrate of the wildflysch basin. Shear sense inversion is documented from top-to the ENE to top-to the WSW across a shallowly S-dipping, hectometer-thick shear zone precursor to the Roquessels fault, which itself records later localized dextral-normal slip at the margin/floor of the wildflysch basin (Figure 2). Dextral-normal shearing is also recorded along the décollement flanking the gneiss dome and that steepened as a result of F2 folding and dome amplification (Figure 2). Relationships between meter-scale olistoliths and their host sediments as well as earlier stratigraphic/sedimentologic observations (Engel *et al.*, 1981. Bull. BRGM) would be consistent with the wildflysch basin having been preferentially fed from the WSW (Fig. 3).

Pervasive top-to-the ENE shearing and later combination of dextral-normal shearing, F2 upright folding and dome amplification along the same direction indicate orogen-parallel extension followed by installation of a right-lateral transtensional regime linked to the activation of the Cévennes fault. Our results, together with preliminary investigation in the Mouthoumet massif, suggest that late (Namurian-Westphalian?) wildflysch sedimentation took place during dextral transtension accommodated along the inner northern limb of the Ibero-Armoric syntax. Early top-to-the ENE shearing contributed to the amplification of the recumbent folds and could even have caused fold nappe tectonics.

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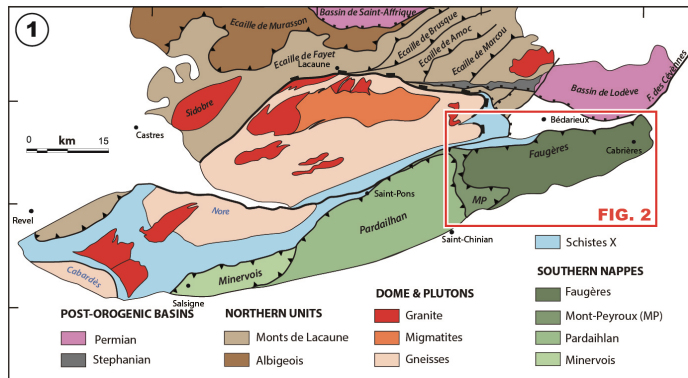
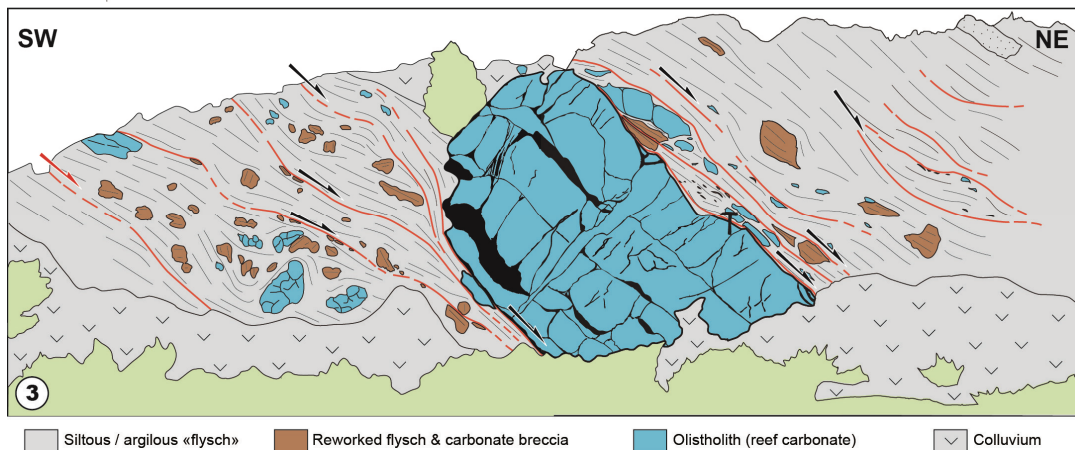
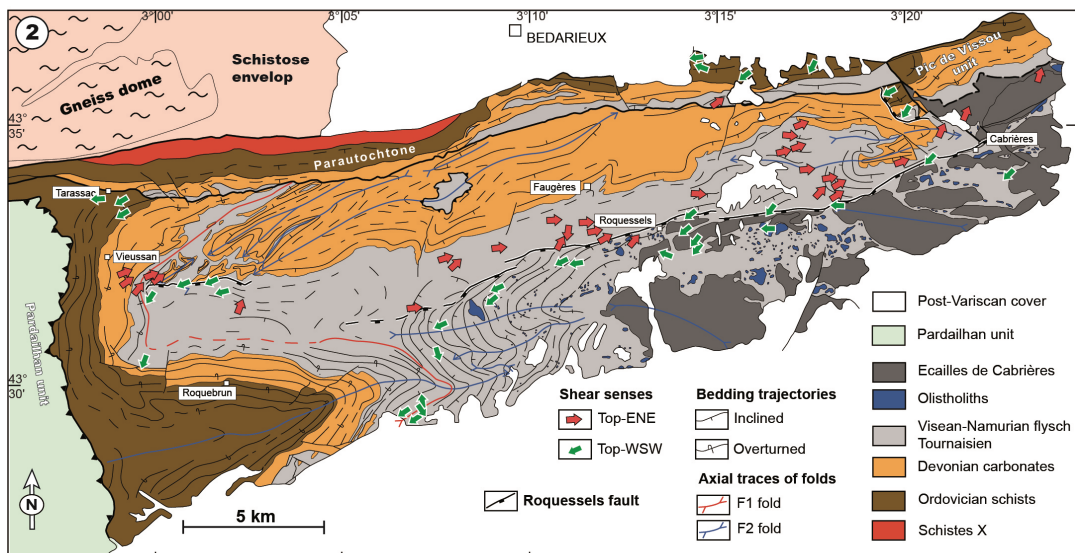


Figure 1. Simplified structural map of the Montagne Noire massif, Southernmost Massif Central. The interpretation shown is that of Arthaud (Publ. USTELA, Montpellier, 1970), who distinguished a Faugères and a Mont-Peyroux nappes on the southern flank of the dome.

Figure 2. Geology, structure and ductile kinematics of the lower unit. Geology and beddings compiled from 1/50 000 scale geological maps and Engel et al. (Bull. BRGM, 1981). The long normal limb of the F1 recumbent fold includes the former right side up Faugères nappe (Fig. 1), whereas the inverted limb of the fold was earlier included into the Mont-Peyroux nappe (Fig. 1). The Ecailles de Cabrières are large right side up slabs considered as the largest and latest olistoliths.

Figure 3. Gliding emplacement kinematics of an olistolith near Vailhan (width of view: ca. 15 m).



New U-Pb and Hf zircon data from the eastern Massif Central: From Gondwana to Pangea in a nutshell

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Terrains involved in the European Variscides were mostly derived from the north Gondwana margin. The French eastern Massif Central (EMC) is made of a complex nappe stack. Toward the end of the orogeny, these units were involved in a large-scale thermal event that caused crustal melting, granitization and the rise of a large migmatitic core complex, the Velay Dome (Fig. 1A).

In the east side of the Velay Dome, the Tournon syncline is a klippe of migmatitic paragneisses of the Lower Gneiss Unit (LGU) affected by the Velay-related melting upon which rests amphibolites, orthogneisses and paragneisses of the Upper Gneiss Unit (UGU) containing relicts of HP-HT and crosscut by several generations of granite dikes (Fig. 1A).

We present new LA-(MC)-ICPMS U-Pb and Lu-Hf data from detrital, magmatic and metamorphic zircons from the main lithologies of the Tournon area. Zircon dates range from Archean to Carboniferous and display peaks at 2.6-2.8 Ga, 1.9-2.1 Ga, 950-1050 Ma, 550-700 Ma, 480 Ma, 340-350 Ma and 325-305 Ma (Fig. 1B). These dates correlate with well-known zircon-forming and geodynamic events.

The protoliths of the Velay granite and the LGU have magmatic (orthogneisses) or maximum depositional (paragneisses) ages of ca. 550 Ma, while those of the UGU are ca. 480 Ma. This data confirm that the UGU and the LGU of the Tournon klippe not only differ in metamorphic histories but also in origin. Hf isotopes and zircon Th/U ratio suggest that the Cadomian magmatism (~550 Ma) resulted from extensive crustal melting rather than typical Andean-type mantle melting. An overall extensional setting possibly

promoted by slab roll-back would be consistent with available data from the EMC and nearby Cadomian massifs (Maures, Pyrenees). After a gap in the zircon record, magmatism resumed at ~480 Ma with bimodal magmas of crustal and mantle origins. It correlates with a well-documented extensional regime all along the north Gondwana margin that led to the opening of the Rheic Ocean as well as smaller epicontinental seas with local ultra-thinned continental crust (e.g. Galicia-Brittany or Massif Central-Moldanubian "Ocean").

From a comparison of zircon U-Pb dates, Th/U ratio and Hf isotopes from paragneisses with penecontemporaneous Cambro-Ordovician sediments across north Africa, we suggest that the Precambrian paleogeographic position of the EMC was most probably nearby today's Israel.

In the UGU, metamorphic zircon rims dated at 350-340 Ma most probably constrain the timing of MP-MT metamorphism that followed the HP-HT event. This is interpreted as the age of the nappe stacking. The dikes at crosscutting the base of the UGU indicate that crustal melting started at ca. 320 Ma, contemporaneous with the emplacement of the nearby peri-Velay Tournon porphyric granite. Small scale crustal melting (dikes) appears to have been continuous until ca. 308 Ma when the widespread melting led to the emplacement of the Velay granites and the migmatitization of the LGU.

The diversity of the lithologies encountered in the Tournon area, that are representative of those of the EMC, provide us with a unique time-integrated perspective on geodynamic and geologic events that have shaped and built today's local crust (Fig. 1C).

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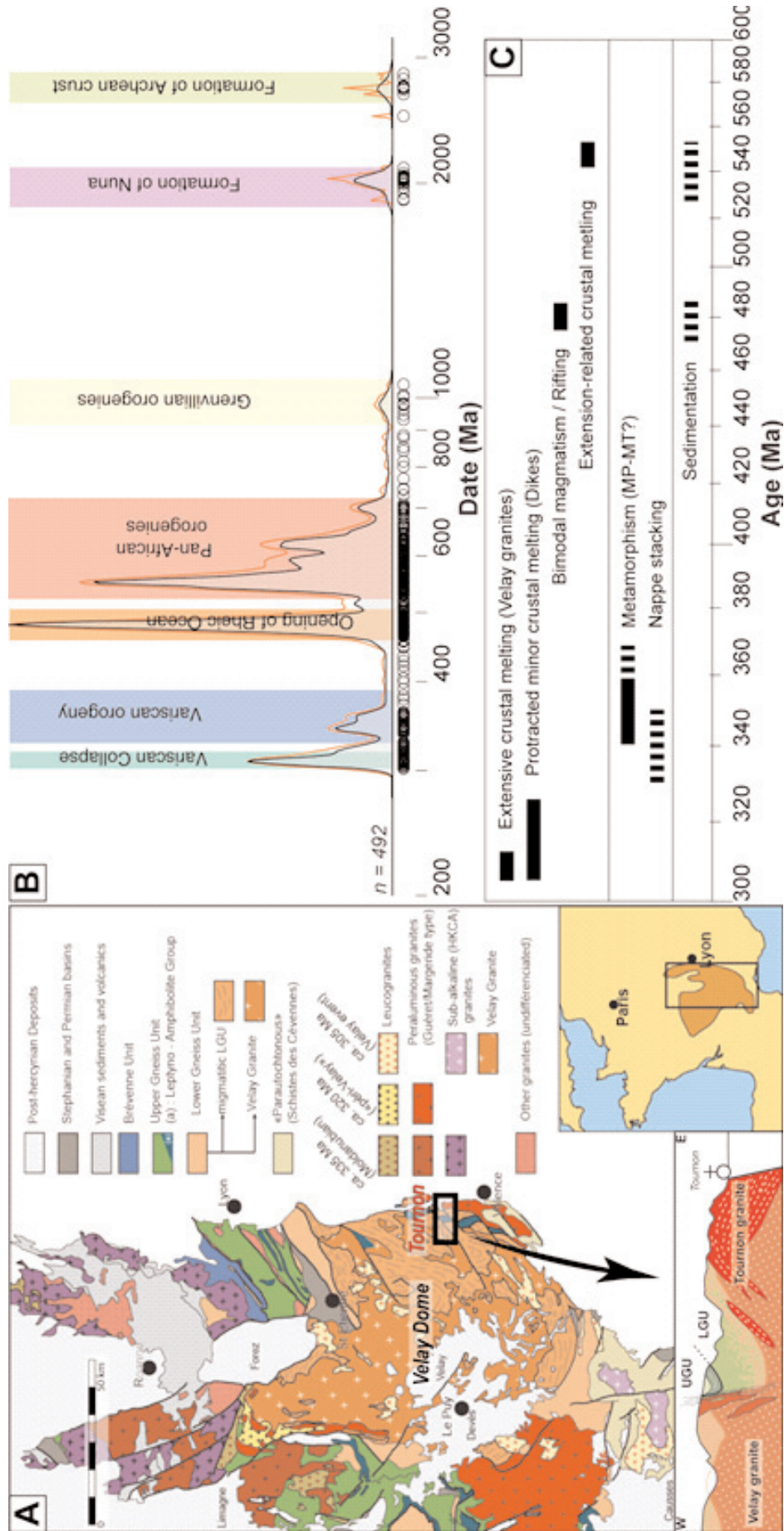


Fig. 1.- (A) Simplified map of the east Massif Central with location and cross section of the Tournon syncline. (B) Density plot of all concordant U-Pb zircon dates from the Tournon area showing the main zircon forming events. (C) Synopsis of sedimentary, metamorphic and magmatic events recorded by zircons from the Tournon area.

Variscan strain field and kinematics of the Pyrenees

COCHELIN Bryan^{1,3}

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Due to the presence of Pennsylvanian “syn-orogenic” flysch deposits, the Variscan crust of the Pyrenees is considered as belonging to the foreland of the Variscan belt. This interpretation fails to explain the high temperature metamorphism and intense variscan deformation in the Pyrenees. This domain is characterized by a structural contrast between an upper crust with steep fabrics and tight upright folds (superstructure) and a middle crust showing subhorizontal foliations taken into domal structures (infrastructure). Various conflicting models based on local studies were proposed to explain these characteristics. In order to obtain an integrated view of this segment of the Variscan belt, we built a large-scale deformation model of the Variscan crust of the Pyrenees, based on an extensive compilation of fabric data and new structural observations.

The large-scale strain field underlined by steep foliation trajectories is homogeneous and consistent a first-order anastomosed network of steep longitudinal shear zones. The major shear zones are roughly E-W trending, kilometre-thick, amphibolite to greenschists facies mylonites with reverse-dextral kinematics. Another set of shear zones consists of decameter-thick low-temperature mylonites oriented around N130°E, which do not significantly affect strain trajectories on a regional-scale. In the superstructure, the regional foliation roughly parallels the major shear zones that commonly coincide with lithological heterogeneities. Lower strain lense shape domains bounded by the shear zones network host mainly gneiss domes forming the infrastructure and plutons intruding the superstructure. Away from the shear zones, the superstructure is characterized by steep foliation planes bearing down-dip stretching lineations and C' type

shears with north-side up kinematics. Plutons' contact aureoles tend to focus dextral strike-slip component of shearing. The infrastructure is characterized by a dominant longitudinal sub-horizontal stretching lineation trending N80 to N110°E. The shear planes are filled by syn-kinematic leucosomes and granites, attesting that this shearing is coeval with partial melting. Strain localization occurs on domes' envelop along syn-melt to retrograde greenschists facies shear zones showing orogen-normal (N350-20°E) stretching lineations and apparent normal sense of shear. These shear zones are later reactivated by part of the reverse-dextral shear zone network during dome amplification by folding due to regional shortening.

Late steep shear zones formation, penetrative deformation and pluton emplacement in the superstructure are kinematically compatible and would record bulk homogeneous orogen-normal shortening combined with vertical stretching within a dextral transpressive framework. Such a deformation pattern in the superstructure is not compatible with orogen-normal extension recorded by the infrastructure and may have been superimposed onto early extension. However, all the deformation patterns described here have developed over a short period of time (310 and 290 Ma) encompassing the formation of the cantabrian orocline. Space and time strain partitioning in the Variscan crust of the Pyrenees have accompanied orocline amplification, with late diffuse dextral Pyrenean transpression having taken place along a flank or at the core of the orocline during its latest stages of development. Our work attests to a Late Variscan age for the formation of the main shear zones in the Paleozoic crust of the Pyrenees. Meso-Cenozoic tectonics only led to local reactivation of such shear zones.

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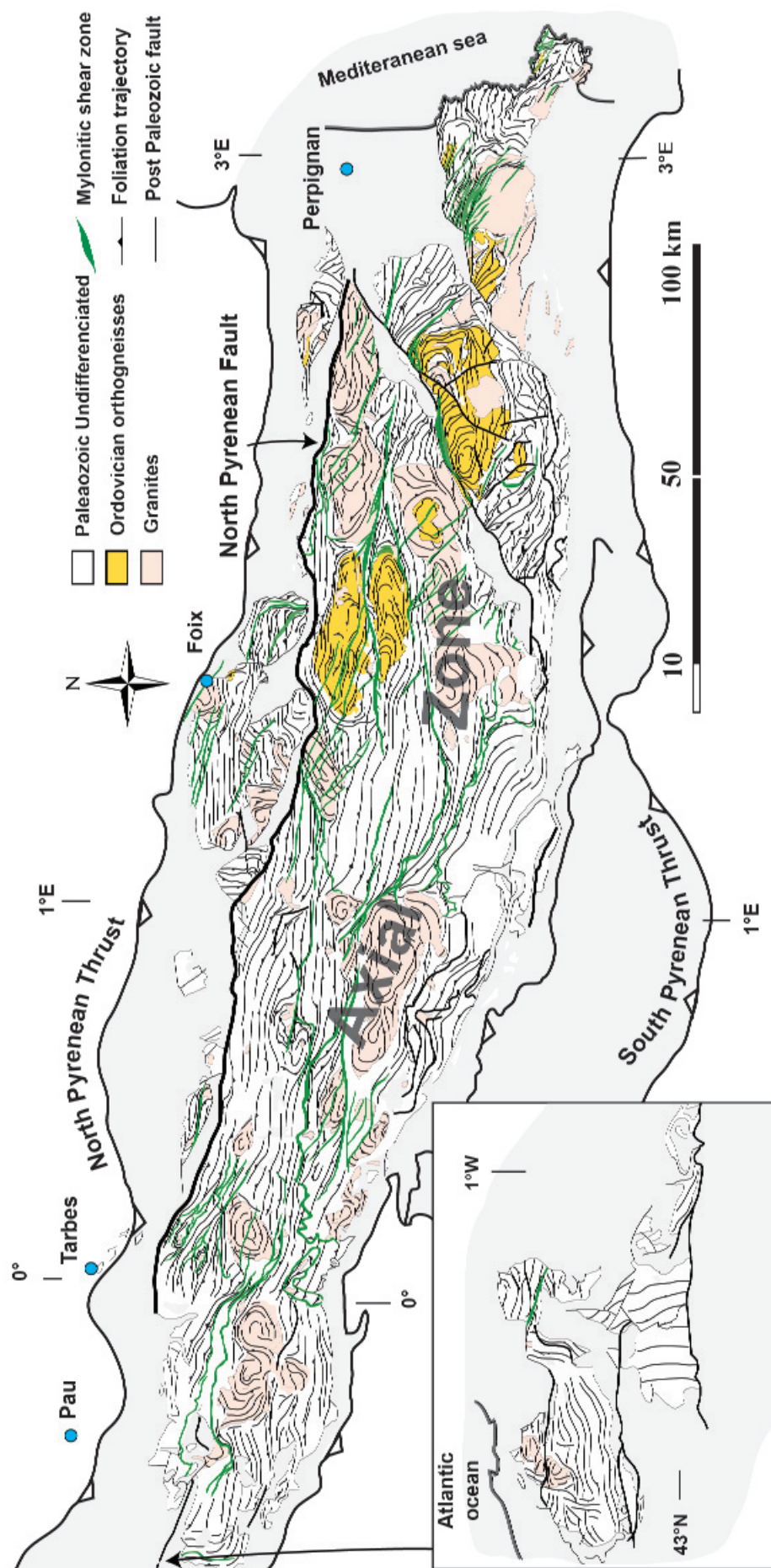


Fig. 1.- Simplified strain field of the Variscan crust of the Pyrenees

CAMBRO-ORDOVICIAN UNCONFORMITIES IN THE CENTRAL-IBERIAN ZONE; EXTENSIONAL OR COMPRESSIONAL PROCESS ?

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One of the main features of the Central-Iberian Zone is the relation between the lower Ordovician and the Cambrian or Upper Proterozoic rocks (the "Sardic deformation"; Lotze, 1956) which is marked by two unconformities: the upper Iberian one between the Armorican Quartzite Formation and underlying early Ordovician units and the Toledanian unconformity between these units and pre-Ordovician basement (Gutiérrez-Marco *et al.*, 2002). The latter recognition that the Sardic unconformity in Sardinia type locality have a younger intra-Ordovician age, led to consider that Toledanian unconformity designation should be used instead of Sardic one (Gutiérrez-Marco *et al.*, 2002). Due to the long use of "Sardic deformation" expression in Iberian and to the possibility of diachronism between Iberia and Sardinia such expression continue to be used it in a sensu latu (Romão *et al.*, 2005).

The genetical mechanisms for these unconformities are still highly debatable: general extension along the northern Gondwana passive margin (e.g. Dias da Silva, 2014), or a transient inversion event (Romão *et al.*, 2005)? To choose between models is difficult because the pre-Ordovician structures are poorly known.

Although the geometry of the pre-Ordovician folds are often considered as open folds (e.g. Díez Balda, 1986), sometimes with box-fold geometry (Ribeiro, 1974), high angular relations (Ribeiro, 1974; Dias da Silva, 2014), or even reverse limbs situations (Rodríguez Alonso, 1985) have been found. Recent work in northern Portugal (Marão and Poiães sectors) shows the absence of the Iberian unconformity and that the strongly deformed zones induced by Toledanian deformation are restricted to narrow bands bounded by wide regions of negligible deformation. Thus, most of the Toledanian unconformity appears as disconformities, with angular unconformities restricted to

narrow bands: overlying the Toledanian unconformity a Lower Ordovician conglomerate with pebbles of pre-Ordovician rocks is pervasive.

Previous regional geometry, mainly the common reverse limbs prior to the Variscan deformation, can't be explained only by rotation of blocks above normal faults as often considered. However it should be the expected relation in a situation of inversion tectonic. This compressive event could have been a transient inversion in the northern Gondwana Cambro-Ordovician global extension (Romão *et al.*, 2005). The Toledanian deformation increase towards south where the Iberian unconformity is also strong.

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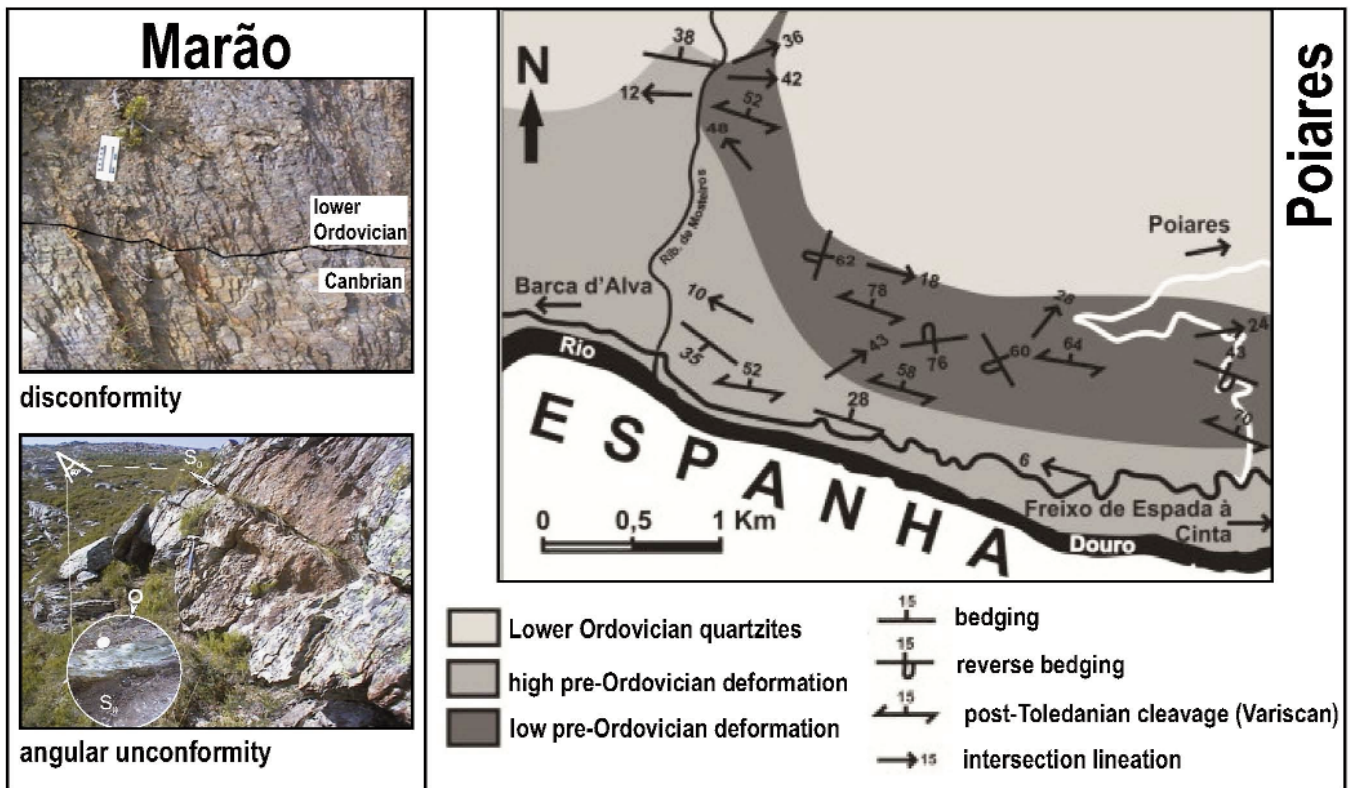
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Mg-K magmatic suites as a tool to scan the composition of the Variscan orogenic mantle, case studies from the French Massif Central

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Post-collisional Mg-K-rich magmatic rocks are well-represented throughout the Variscan belt. They occur either as hypovolcanic dykes and sills (lamprophyres) or deep-seated plutonic intrusions (called “vaugnerites” in the French Massif Central). Such rocks share the same key characteristics: marked enrichment in both compatible (Mg, Fe, Ni, Cr) and incompatible (K, Rb, Ba, Sr, REE) elements. This signature has long been interpreted as pinpointing interactions between a mantle-derived melt and the continental crust, either directly in the mantle source (melting of metasomatized lithospheric mantle domains) or/and during magma ascent in the orogenic crust (contamination). We provide new constraints on those issues using whole-rock geochemical and zircon Hf-O isotope data from vauagnerites of the French Massif Central.

Vaugnerites that were mechanically mixed with the crust-derived Margeride monzogranite display $\epsilon\text{Hf}_{(311 \text{ Ma})}$ significantly lower than the granite magma, which rules out contamination and rather argues for derivation from an enriched mantle with crust-like, non-radiogenic Hf isotope signatures. It entails that the trace elements and isotopic compositions of vauagnerites are mainly controlled by source processes (degree, depth of melting, heterogeneities in the orogenic lithospheric mantle) and fractionation.

The Cévennes Médiannes area offers a unique possibility to investigate those processes. Indeed, zircon U-Pb dating (Laurent *et al.*, this conference) showed that in this region vauagnerites synchronously intruded the middle crust at ~306 Ma, yet having diverse major- and trace-element

compositions. Thus, investigated samples represent magma batches coevally extracted from a possibly heterogeneous mantle column. Major elements compositions do not match any fractionation or contamination trend but comparison with experimental melts from metasomatized peridotites at 1 GPa suggests the variability observed arose from polythermal melting of variably enriched mantle domains. Correlative La enrichment with Yb depletion typically document lower degrees of melting in deep garnet-bearing sources. Zircon $\delta^{18}\text{O}$ values spread over 2 units (from +6.3 to +8.3) showing that crustal contaminants present in the lithospheric mantle experienced a weathering cycle and involved a diversity of materials, possibly ranging from upper to lower crustal lithologies as inferred from variable Th/La ratios. The relative amount of crustal materials in the source was estimated by: (i) calculating the fraction of crustal material required to balance the higher Hf contents of metasomatized peridotites relative to a depleted mantle reference; (ii) isotopic mixing calculations involving depleted mantle and upper to lower crustal endmembers aiming at reproducing the $\epsilon\text{Hf}_{(306 \text{ Ma})}$ of 62.6 to 65.3 recorded by vauagnerite zircons. Both methods suggest that the crustal component represents less than 12 wt.% of the bulk, metasomatized mantle source. Crust-mantle interactions possibly resulted from subduction of Gondwana-derived sediments (as indicated by Hf model ages in excess of 1.3 Ga for the required crustal components) and/or delamination of the restitic lower crust but there is any time constraint on mantle enrichment event(s).

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Amphibole bearing migmatite from Variscan Sardinia (Italy) and its constraints on partial melting

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A lens-shaped body of amphibole-bearing migmatite in the metamorphic basement of NE Sardinia is in contact with migmatized orthogneiss and Al-silicate (fibrolite + kyanite) bearing migmatites. Oscillatory zoning and Th/U ratios (0.40-0.70) in zircons suggest an igneous origin for the amphibole-bearing migmatite protolith, whose emplacement age has been dated at 461 ± 12 Ma by Pb-Pb isochron on zircon separates (Cruciani *et al.*, 2008). This migmatite shows discontinuous banding defined by well-foliated, biotite-rich mesosomes and poorly-foliated, quartz-feldspathic leucosomes parallel to the main foliation or folded by the D_2 deformation. The leucosomes also occur as discordant leucosomes, pods or patches up to 30-50 cm long, or pegmatite-type leucosomes. Tonalitic leucosomes consist of quartz, plagioclase, \pm amphibole, \pm garnet (<1-2 vol.%), minor biotite (<5 %), rare K-feldspar and apatite, zircon and titanite as accessory phases. Granodioritic/granitic leucosomes (K-feldspar \sim 20-30 %) are found in two lenses entrapped in the adjacent migmatized orthogneiss. The mesosomes consist of quartz (35-45 %), plagioclase (35-45 %), biotite (10-20 %), amphibole (<5 %), and garnet (<2 %). Amphibole (K-rich-pargasite, $X_{Mg} \sim$ 0.4-0.5) occurs in the leucosomes as euhedral crystals rich in plagioclase, quartz, and small garnet (Alm_{51-53} ; Prp_{-7} ; Grs_{32-34} ; Sps_{-7} mol.%) inclusions. Garnet pre-dates partial melting, as indicated by the Y depletion and by the differences in the concentrations of HREE, V, Cr, and Y observed in different garnet crystals that testify lack of equilibrium with the anatectic melt. Amphiboles have an inner portion with $Si = 6.25$ a.p.f.u. surrounded by rims of identical composition. However, in some cases, the rims have higher Si content (6.9 a.p.f.u.). Some amphibole rims have also higher REE and negative Eu anomalies as compared to their cores which, in turn,

exhibit lower REE and positive Eu anomalies (Cruciani *et al.*, 2014). The cores crystallised from or in the presence of melt; adjacent rims with negative Eu-anomalies developed in coexistence with a Eu-depleted melt that had experienced plagioclase fractionation. Massonne *et al.* (2013), contouring the Na/K and Si/Al ratios in melt in a P-T pseudosection calculated for average composition of the protolith, obtained P-T conditions indicative of partial melting \sim 1.3 GPa, 700 °C. The P-T pseudosection approach for the leucosome composition yielded P-T conditions \sim 1.05 GPa and 700 °C for the crystallization of amphibole in the leucosome melt, and 0.9 GPa and 680°C for complete crystallization of this melt. The resulting clockwise P-T path implies that the melt must have resided in the rock during exhumation from about 45 to 30 km depth, over a long period of time. The ^{40}Ar - ^{39}Ar method on amphibole separates yielded a slightly discordant age profile with an error-weighted mean age of 317.4 ± 2.0 Ma. The same method on biotite gave a hump-shaped age spectrum, most probably influenced by interlayered chlorite. The total gas age is \sim 283 Ma, considered to be a minimum Ar age for the biotite.

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Is the magnetic Ibero-Armorican arc the trace of a Cambro-Ordovician aborted rift ?

DE POULPIQUET Jacques

The South Armorican continental shelf (SACS) is characterized in geophysics by strong magnetic anomalies (de Poulpiquet and Lefort, 1989) extending from the edge of the continental shelf in the West to the northern border of the Aquitaine Basin in the East (Fig. 1a) with an associated seismicity around Oléron Island (Fig. 1c).

The large-scale component of these magnetic anomalies (wavelengths longer than 100 km) has been poorly studied so far: in a first study de Poulpiquet (1990) modeled the strongest anomaly in the South of Belle-Ile and interpreted it as a slab-like body of large width (70 km) on the profile L315 (Fig. 1a). Then he used the upward continuation of the magnetic field to a height of 13 km above sea level (Fig. 1b) to show the regional character of the magnetic anomalies of the SACS (de Poulpiquet, 2012). To model the geological structure responsible for this regional anomaly, data processing of a 360-km-long profile (Profile T on Fig. 1a) was performed using Fourier and wavelet transforms. The source of the long-wavelength component is interpreted as a slab-like body deeply rooted (10 km) under the continental shelf.

On the other side of the Bay of Biscay the Eastern Galicia magnetic anomaly (EGMA) in Northwest Spain shows similar features (wavelengths, intensities) and models of the magnetic source (slab-like bodies):

- in a first study Aller (1986) interpreted the EGMA to be at the origin of an intrusive igneous body and then noticed that it would be “produced by a middle to lower crustal layer emplaced with a ramp-flat-like geometry in higher crustal layer” (Aller *et al.*, 1994);
- regarding the Lugo and Sanabria gneiss domes (Fig. 1a) Ayarza and Martinez Catalan (2007) explained the occurrence of the EGMA to be produced by “a large volume of low-density migmatites and associated inhomogeneous granites”;
- regarding the central part of the EGMA between both the domes of Lugo and Sanabria, de Poulpiquet (2012)

interpreted EGMA as two different magnetic sources: a deep heavy and magnetic body, compatible with both models of Aller (1986) and Aller *and al.* (1994) and a shallow and low-dense magnetic body, compatible with the migmatites source in the model of Ayarza and Martinez Catalan (2007). In this case the migmatites could be produced by partial melting of the deep body (mafic rocks contained in the intrusive igneous rocks of the first model of Aller (1986)). Such an assumption the presence of two levels of depth of magnetic bodies is validated also on the SACS.

Plotted on a pre-opening fit of Bay of Biscay, the 800 km long magnetic ibero-armorican (MIA) arc defined by the SAMA and those of EGMA fits well with a larger geological structure: the Ibero-Armorican arc. This so-defined magnetic arc is always along this trace between two major geological belts of Ibero-Armorican arc: a porphyroid belt and a cambro-ordovician trough (Fig. 2) emplaced during the Cambro-Ordovician extension. Thus the MIA arc could be related to this extension and possibly represents the trace of a Cambro-Ordovician aborted rift.

The existence near the EGMA of a very deep trough (the West Asturian-Leonese Basin), which is filled up with more than 10 km of Cambro-Ordovician sediments (Matte, 1968) suggests a very strong thinning of the continental crust and the intrusion of mafic rocks. So the West Asturian-Leonese Basin whose origin is poorly explained would be re-interpreted in this model as an aulacogen resulting from the opening of a northern rift extending as far as South Brittany. The opening of this rift could have occurred during the Late Ordovician, when the West-Asturian trough suddenly deepened, leading to turbiditic sedimentation. The unimodal northward paleocurrent directions of turbidites (Fig. 2) in the Agueira Formation (Pérez-Estaún and Marcos, 1981) would thus be explained by the deepening of the trough northwards, correlated with the opening first of a northern rift on the SACS.

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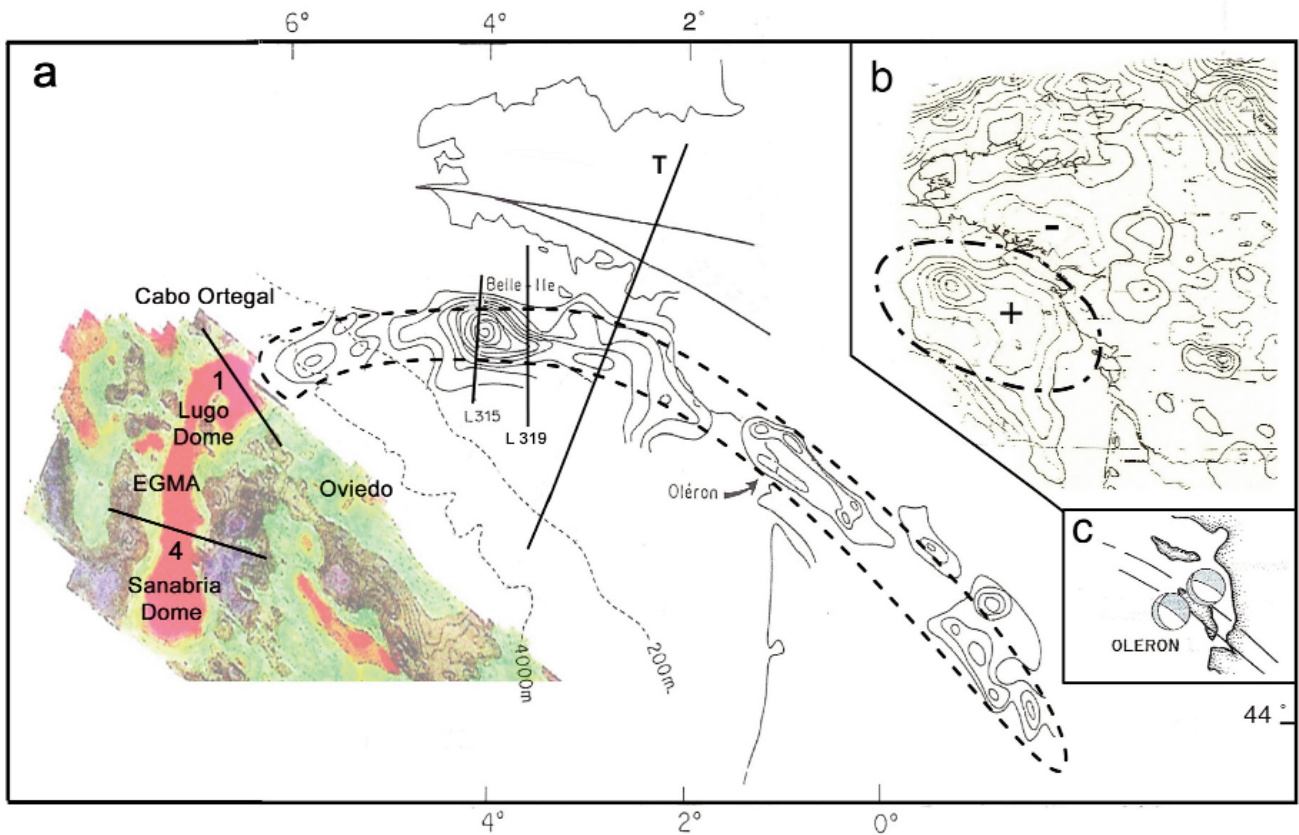


Fig. 1.- a) Location of the magnetic Ibero-Armorican (MIA) arc based on anomalies of the total magnetic field measured at 3 000 m elevation in France (surrounded by dashed line) and in Northwest Spain (coloured magnetic map). Magnetic profiles studied: T = transverse magnetic profile, profiles L315 and L319 (de Poulpique, 1990), profile 1 (Ayarza and Martínez-Catalán, 2007), profile 4 (Aller et al., 1994). b) Map of the total magnetic field anomaly continued upward to an height of 13 km (Institut du Physique du Globe, Paris) with location of the low-frequency magnetic zone (surrounded by dashed-dotted line) observed above the south-Armorican continental shelf. c) Focal mechanisms for earthquakes at Oléron Island in 1972 and 1977.

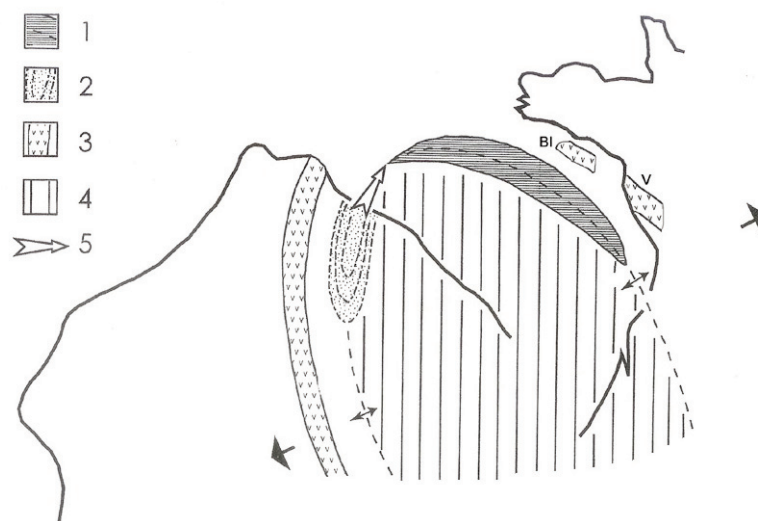


Fig. 2.- Proposed geodynamic evolution of the internal part of the Iberian-Armorican arc during the Cambro-Ordovician. The following features are plotted on a pre-opening fit of Bay of Biscaye: 1: oceanic crust ? 2: Asturo-Leonese trough (aulacogen ?) 3: Early Ordovician volcanism : porphyroids of Ollo de Sapo (Spain), Belle-Ile (BI) and Vendée (V) 4: Ebro-Aquitainian paleogeographic domain 5: transport direction of turbidites in the Agüeira Formation.

Ophiolite Enigma resolved?

DEWEY John

Ophiolite complexes are the result of organized sea-floor spreading and are confined to the Phanerozoic, mainly peaks in the Early Ordovician (e.g. Bay of Islands and Shetland), the Early Jurassic (Balkans), and the Mid-Cretaceous (e.g. Oman and Troodos). However, enigmatically, their non-MORB petrology and geochemistry have a strong arc affinity, especially their boninites (high Si and Mg, high temperature, low pressure, wet andesites, rocks that are characteristic of the fore-arcs of oceanic arcs). A model based upon data from ophiolites and modern west-Pacific arcs is that of an oceanic ridge transecting the fore-arc to meet the trench in an RTT triple junction. As spreading proceeds, the fore-arc and arc lengthen giving oblique slip vectors at the trenches. Ophiolite obduction occurs discontinuously, only where an ophiolite fore-arc collides with a rifted continental margin or any margin without a subduction zone. Most, if not all, oceanic trenches originate by conversion from oceanic transforms/fracture zones, yielding two RTT triple junctions, one with ridge subduction on the lower plate, the other generating a lengthening, ophiolitic fore-arc. As the fore-arc lithosphere cools and thickens, it becomes serpentinized; serpentinite diapirs rise to the ocean floor. The style of arc-continent collision depends upon the age of the ophiolitic fore-arc; young ophiolites are easily obducted as thin sheets, whereas older thicker fore-arcs bulldoze continental margins, with the arc over-riding the fore-arc. Obducted ophiolites have thin (<150 m) discontinuous sheets of "so-called" metamorphic aureoles (2-pyroxene

granulites and garnet amphibolites) attached to the harzburgites or lherzolites along their bases. These are not metamorphic aureoles *sensu stricto*; they originated from a MORB source at 10 kb/1 100 °C from the subducting slab and were later attached to the base of the obducting ophiolite. The principles are illustrated by the Early Ordovician Bay of Islands Complex in western Newfoundland from which a coherent model is developed including pre- and post-obduction slip vectors of relative plate motion. The Lizard ophiolite complex originated at about 400 Ma and was obducted as a hot sheet between 390 and 370 Ma. A new model for the structure and emplacement Lizard will be presented.

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Lateral escape tectonics in the Variscan Orogen: A new approach for the emplacement of the Allochthonous terranes and for the birth of the Central Iberian Orocline

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The Variscan belt is formed by different terranes amalgamated in the continental collision between Laurussia and Gondwana to form Pangea supercontinent [e.g. 2]. This orogeny was responsible by a continuous deformation that lasted for ~90 Ma, with changing tectonic regimes triggered by the migration of the orogenic front into new domains.

In this work, we propose the formation of an extrusion-fan as a product of lateral escape tectonics in the Western Variscan chain (Fig. 1A), that provides a new approach on the origin and the tectonic emplacement of the NW Iberian Allochthonous Terranes (IAT) and the birth of the Central Iberian Orocline (CIO) [11].

The early stages of tectono-metamorphic Variscan imprint in NW Iberia are preserved in the IAT. In the Middle-Upper Devonian [e.g. 2] the IAT units underwent high pressure conditions and exhumation processes, along the Variscan accretionary prism that overrode the N Gondwana margin [e.g. 10]. This early Variscan deformation can be traced in Central Europe [e.g. 8] where it is associated to the establishment of the Variscan continental collision (Fig. 1B).

The advance of the orogenic front in the Devonian-Carboniferous to the more "autochthonous" realms of NW Iberia produced gentle folding (C1) and started the Barrovian metamorphic event (M1); displaying stronger deformation in the Parautochthon (PA) than in the Autochthon [AU, 4] due to its proximity to more active regions (Fig. 1B).

In the Lower-Middle Mississippian, gravitational instability in the inner orogenic zones [e.g. D2 event, in 5] triggered lateral escape of pieces of the accretionary prism (the IAT, Fig. 1C), bounded by low angle detachment faults [6] that expanded obliquely to the orogen trend [9]. They were

carried into NW Iberia using the PA as the lowermost tectonic slice that allowed the extrusion-fan to progress into external orogenic domains. The PA has thrust and pushed marginal syn-orogenic marine basins to the AU [4], forming a piggy-back stack bounded by C2 detachments with the IAT at the top and the AU in its base. This permitted shearing and dragging of the C1 folds in the PA and axis rotations in the AU, developing a nearly concentric fold array around the IAT [e.g. 1], giving birth to the Central Iberian Orocline (CIO) and reaching the peak of Barrovian metamorphism in the AU [e.g. 12].

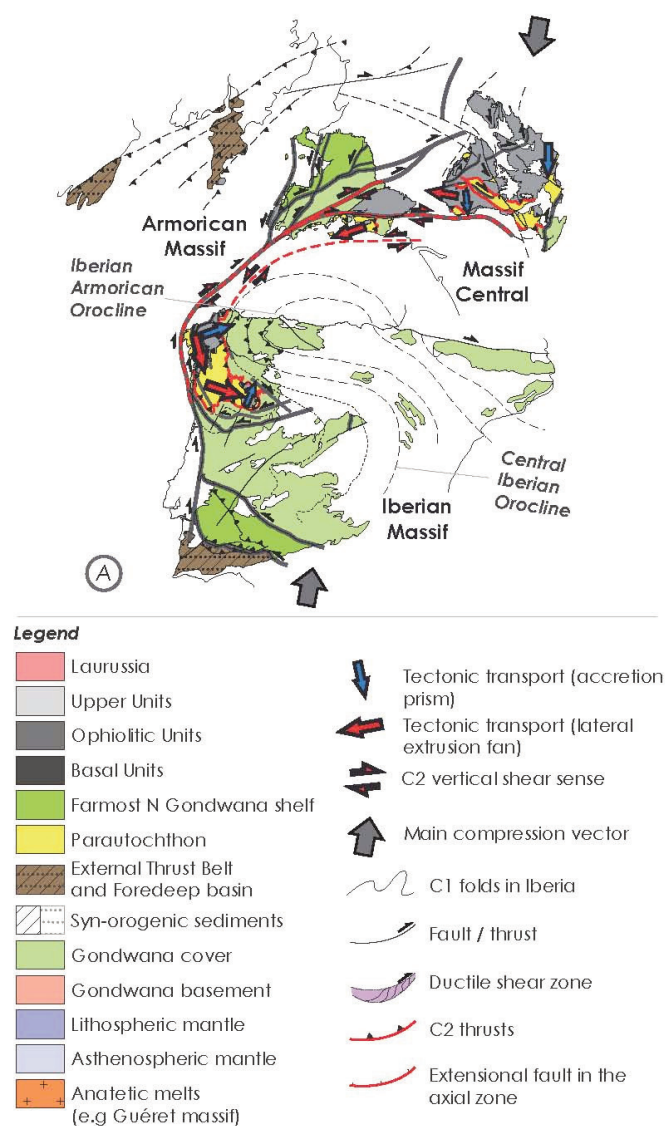
The final orocline geometry (Fig. 1A) was achieved after the NW Iberian syn-tectonic extensional event [E1, 11] and the late-Variscan compressive event (C3) that led to the tightening of the CIO and to the formation of the Ibero-Armorican Orocline [7].

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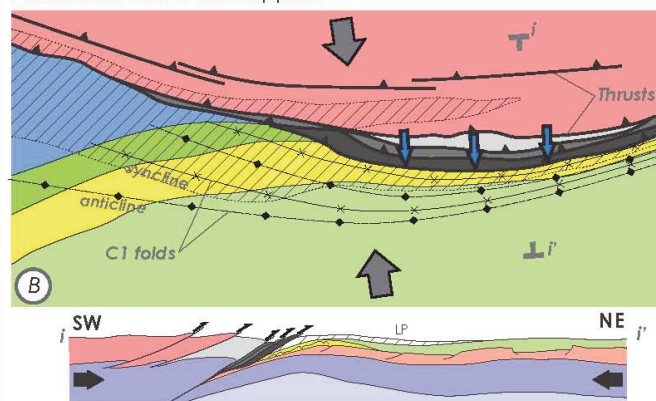
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Famennian-Lower Mississippian



Lower-Middle Mississippian

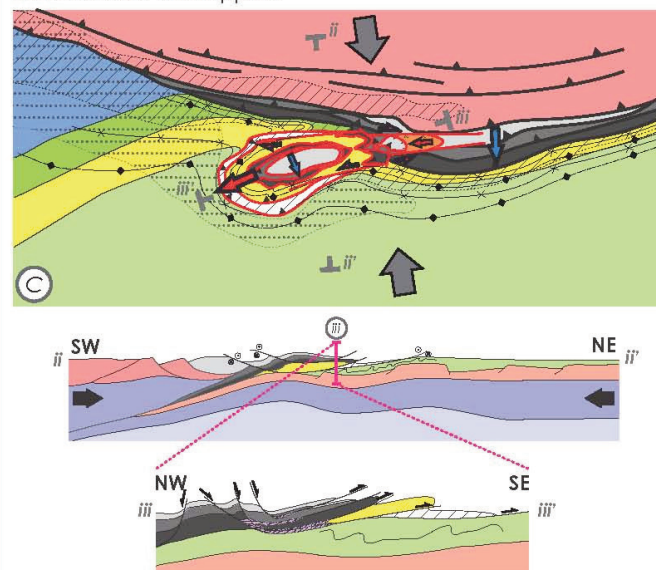


Fig. 1.- Birth of the CIO and origin of the IAT. A) Geometry after the formation of Pangea. Based in [11] and [5]; B) Continental collision and formation of the accretionary prism; C) Lateral extrusion of the IAT. B) and C) Based in [3].

Dextral strike-slip tectonics in Iberia and the Pangeia Assemblage; evidences of the Tardi-Variscan Deformation event in South Portuguese Zone

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The late Variscan deformation event in Iberia (the so-called Tardi-Variscan), active in Stephanian/Permian times, is characterized by an intraplate deformation regime induced by the oblique collision between Laurentia and Gondwana, leading to the Pangeia assembly (e.g. Arthaud and Matte, 1977; Nance *et al.*, 2012); this oblique collision generates a dextral transcurrent deformation regime.

The Tardi-Variscan episode in Iberia is characterized by NNE-SSW strike-slip faults (Fig. 1A), which are considered by the classic works as sinistral strike-slips (e.g. Arthaud & Matte, 1977; Iglésias & Ribeiro, 1981). However, the absence of Mesozoic formations constraining the age of this sinistral kinematics, led some authors to consider it the result of Alpine reworking (e.g. Marques *et al.*, 2002).

Recent studies performed in Almogrove and Ponta Ruiva sectors (South Portuguese Zone, SW Iberia), not only shows that NNE-SSW faults presents a clear sinistral kinematics, but also that this kinematics is related to the late deformation episodes of Variscan Orogeny:

- in Almogrove sector (Fig. 1B), the late Variscan structures are characterized by NNE-SSW sinistral kink-bands, spatially associated with E-W dextral faults. These structures are contemporaneous and affect the previously deformed Carboniferous units ;
- the Ponta Ruiva Sector (Fig. 1C) is essential to constrain the age of deformation because the E-W dextral shears affect the late Moscovian units (Pereira *et al.*, 2007), but not the overlying Triassic series.

These data shows that the NNE-SSW and the E-W faults are dynamically associated and results from the same deformation event. The NNE-SSW sinistral faults could be considered as second order dominoes structures related with first order E-W dextral shears (Ribeiro, 2002). The E-

W structures, which are less developed at mesoscale, have a first order development at the Iberia scale (Fig. 2A):

- a northern deep anisotropy controlling the future Cantabro-Pyrenean chain due to Meso-Cenozoic reworking;
- another lithospheric anisotropy, at south, subsequently associated with the Azores-Gibraltar Fault and the Betic Chain.

On Pyrenean Axial Zone, where the variscan basement outcrops, there are structural and magmatic evidences to a late Paleozoic dextral strike-slip shear zone, which is compatible with the transcurrent regime previously stated (e.g. Carreras *et al.*, 2004; Denèle *et al.*, 2008).

Acknowledgements

The Évora Geophysics Centre, under the contract with FCT (Portuguese Science and Technology Foundation), PEst-OE/CTE/UI0078/2011. Noel Moreira acknowledges to *Fundação Calouste Gulbenkian* for the financial support and FCT PhD grant SFRH/BD/80580/2011.

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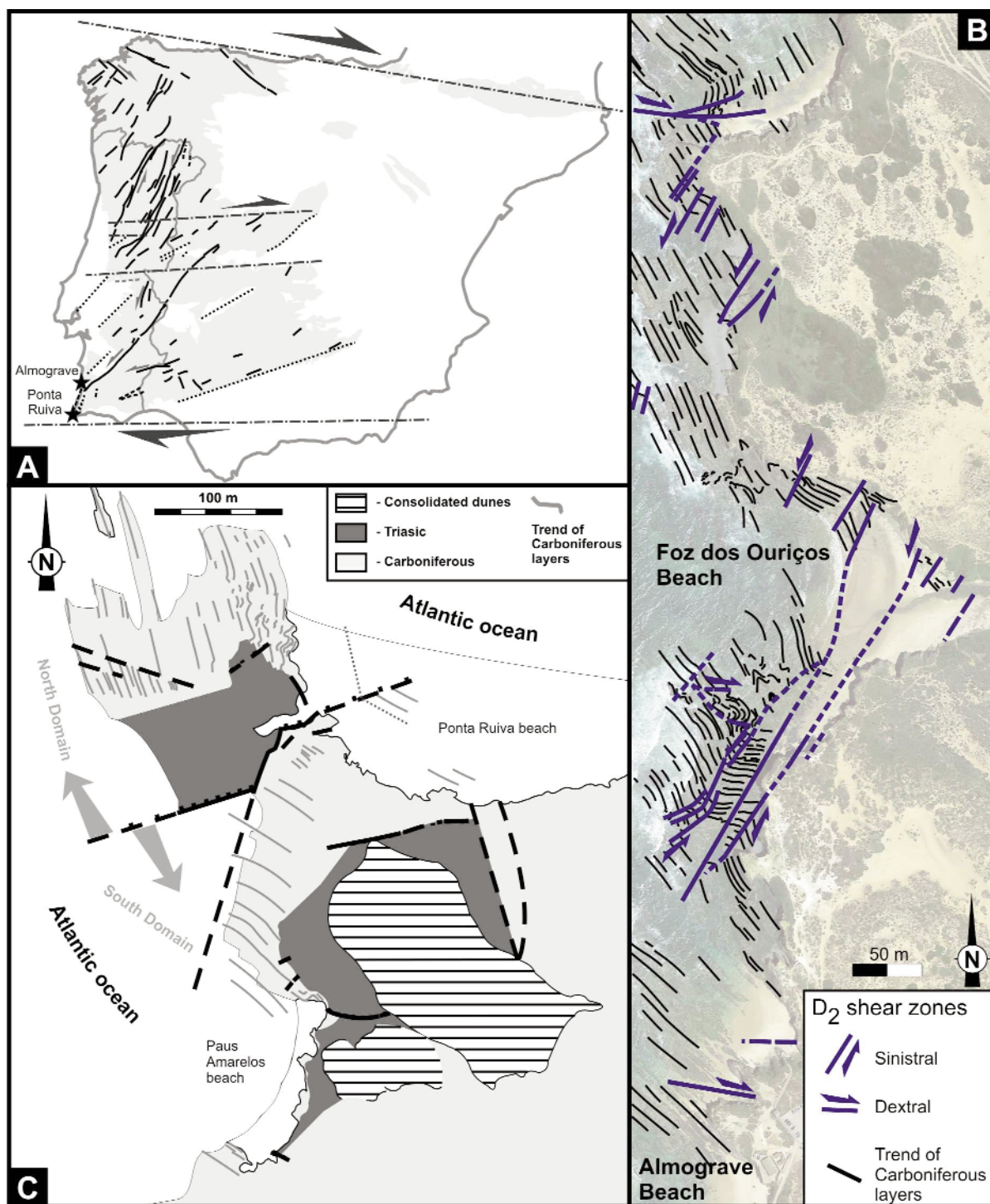


Fig. 1.- (A) Tardi-Variscan shear structures pattern in Iberia (the black stars indicate the studied sectors); (B) Simplified map of Ponta Ruiva sector; (C) Simplified map of Almogrove sector.

CENTRAL IBERIAN ARC; JUST A MODEL?

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The Aerden work of 2004 reopens the interest of a Central Iberian Arc (CIA); however it should be stressed that his proposal of a major curvature of the main variscan structures (Fig. 1) inside the Central Iberian Zone (CIZ), was considered by himself a "very speculative model". Nevertheless, since then several papers support the existence of such first order arcuation in the Iberian Variscides. Although there are some debate concerning its precise pattern (mainly in what concerns the extension of the supposed southern limb), the reconstructions show a general isoclinal shape (Shaw *et al.*, 2014; Martínez Catalán *et al.*, 2014). As the CIA has deeply influenced several recent models concerning the geodynamical evolution of Iberia, it is crucial to discuss some of the data supporting this variscan structure:

- *major fold orientations and tectonic events*- The main CIA pattern is obtained considering that most of the major folds found in the CIZ are due to the regional D3 Variscan event that refold previous D1 structures. Although such interpretation is in clear disagreement with previous published data (see recent reviews in Gibbons & Moreno, 2002; Vera, 2004; Dias *et al.*, 2013), the authors never explain what new data support their position;

- *magnetic anomalies*- Due to generalized Meso-Cenozoic cover that hidden some crucial sectors in the proposed hinge zone of CIA, they use geophysical to understand the basement structures. However, it is not easy to identify the source of such anomalies, because they could correspond to different data. Moreover the late variscan granites are also a major problem in the correlation of older structures;

- *paleocurrents in lower Ordovician Quartzites*- Using sinsedimentary structures they defend that the paleocurrents are subperpendicular to the local strike, indicating that the CIA and the Cantabrian Arc are superimpose in an original linear realm. Nevertheless, although such interpretation is consistent to the Cantabrian

Arc data, the paleocurrents estimated for the supposed southern limb of the CIA presents a much less clear pattern (Fig. 2).

So, some of the main arguments supporting the CIA are highly questionable. Moreover, there are some well established data for the CIZ that can't be understand with such arcuate structure:

- during the Middle Ordovician the sedimentary and faunal data shows a deepening of the basin from S to N (Robardet, 2002);

- there is a strong structural contrast for the main Variscan event (which is D1 and not D3) between the northern and southern sectors of the CIZ emphasizing that they can't be lateral equivalents.

So the existence of the CIA could not be supported by the CIZ data.

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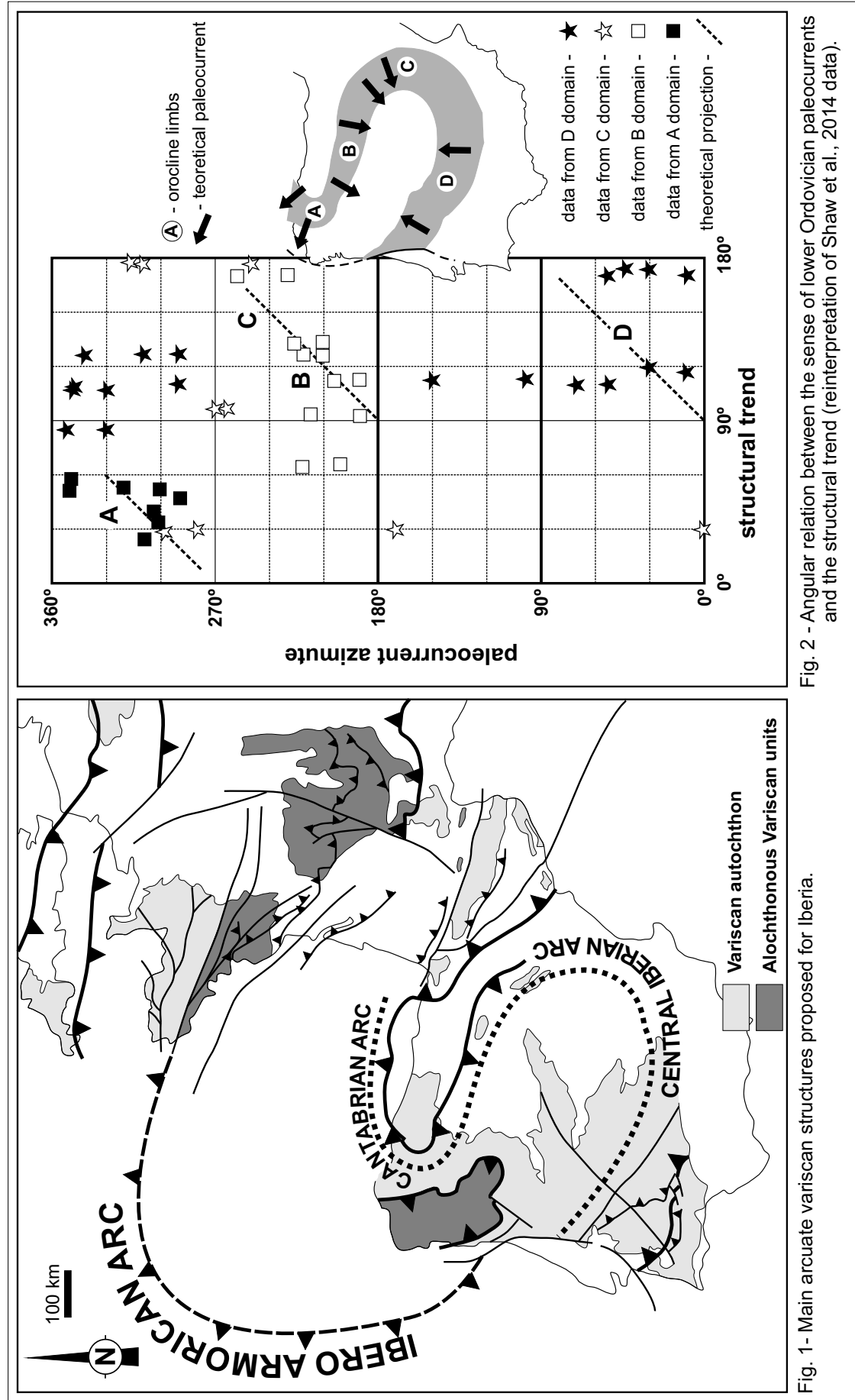
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A window to the crust below Moroccan Massif Central: high temperature crustal xenoliths trapped in Permian lavas

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DAHIRE Mohamed²

Witnesses of the variscan belt are exposed in Morocco in the Northern Mauritanides, the Anti-Atlas and the Meseta domain. It is believed that these domains represent the former Gondwana passive margin and the southern termination of the variscan belt. The Paleozoic series of the Moroccan variscan belt records greenschist to amphibolite facies conditions. The highest metamorphic conditions are observed along the NE-SW trending Western Meseta Shear Zone. However, the Moroccan variscan crust exposes mainly low-grade metamorphic rocks. Crustal xenoliths trapped in magmatic rocks represent an alternative for studying the thermal state of the crust below the Moroccan Massif Central. Xenoliths of sedimentary origin and of high metamorphic grade have been described i) in the late-hercynian granodioritic dykes of the Jebilet massif ii) in the quaternary basalts of the Middle Atlas and iii) in the late-hercynian intrusions of the Central Massif (Zaër granitic pluton and microdioritic dykes of the Mrirt-Khenifra domain). Here we present the petrological study of xenolith samples that have been collected in a microgranodioritic dyke of the later domain, 2 km east of Mrirt. The dyke is ca. 1 m thick and can be followed over a distance of ca. 2 km. This dyke crosscuts a microgranitic dyke that contains xenoliths that have not been selected for detailed petrological analysis.

In the studied area (Fig. 1), the sedimentary sequence in which the dykes are intruded is composed by Ordovician to Devonian detrital sandstones and pelites, shales, and carbonates. Detrital carboniferous stratas are discordant on the Ordovician to Devonian sediments. Finally, the hercynian structures are sealed by Upper Stephanian-Autunian continental redbeds that are affected by late hercynian faulting. Microgranitic dykes and granitoid

plutons crosscut the carboniferous stratas and structures, and are mainly parallel to the schistosity. The final pulse of paleozoic activity is represented by the microgranodioritic dykes that crosscut the schistosity and are therefore considered as post-orogenic, but predates the Triassic deposit, so that a Permian age, confirmed by preliminary LA-ICPMS U-Pb zircon dating, is proposed.

The studied xenoliths are ca. 5 cm in size. Contact with the host lava is usually sharp, although sometimes underlined by a small (ca. 2 mm) reaction zone. Xenoliths are characterized by high Al₂O₃ content (18-31 W%) and low SiO₂ content (44-57 W%). Sample mineralogy include sillimanite, andalusite, garnet, cordierite, corundum, spinel and plagioclase that characterize both the aluminum-rich character of the protolith and low-pressure/high temperature conditions. Petrographic observation (Fig. 2) and thermodynamic modelling point to incipient partial melting, pressure varying from 0.1 to 0.6 GPa depending of the xenolith, and temperature evolution of individual samples in the range 750-1 000 °C (Fig. 3). Therefore, crustal xenoliths sample upper to median variscan crust. The aluminum-rich composition points towards refractory metasedimentary protolith that can be interpreted as due to multi-stage partial melting and melt extraction. Major and trace element analysis precludes extensive chemical exchange between the xenolith and the host lava. Thermal exchange between host lava and the xenolith cannot be excluded, nevertheless, the persistence of similar parageneses in xenolith from lower temperature granitic bodies suggest that the high temperature conditions represent an overall high-temperature field in the variscan crust sampled by xenoliths trapped in the magmas.

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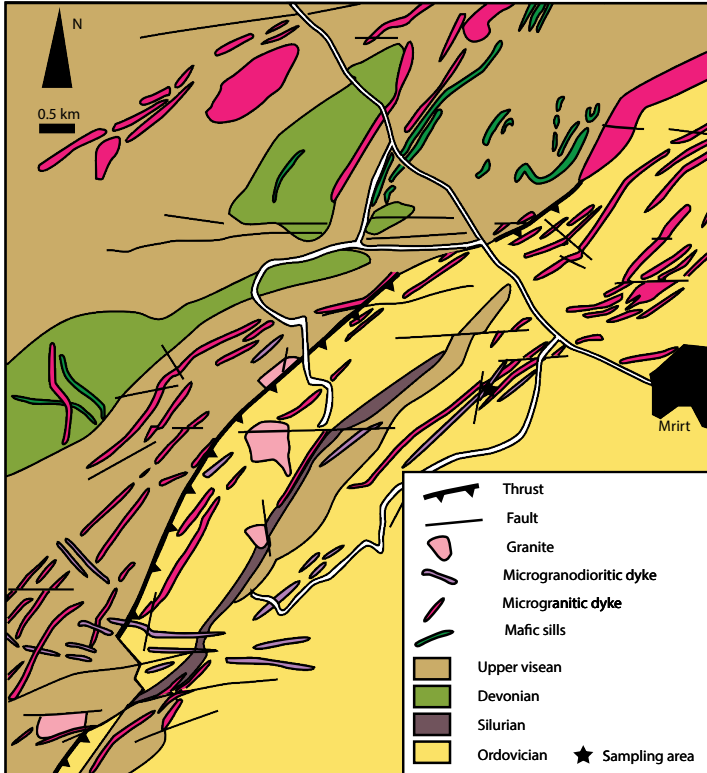


Figure 1. Geological map of the sampling area (d'après Ntarmouchant, 2003)

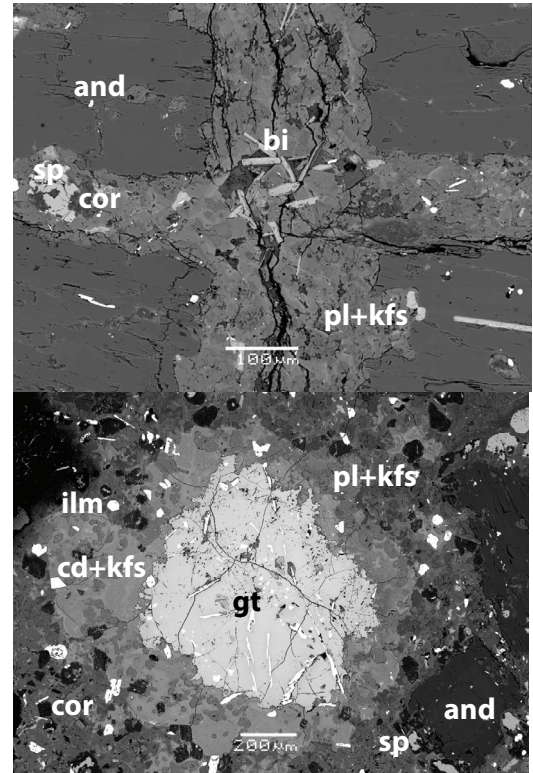


Figure 2. SEM images from sample Ma10. sp spinel; cor corundum; pl plagioclase; kfs alkali-feldspar; bi biotite; gt garnet; and andalusite; cd cordierite

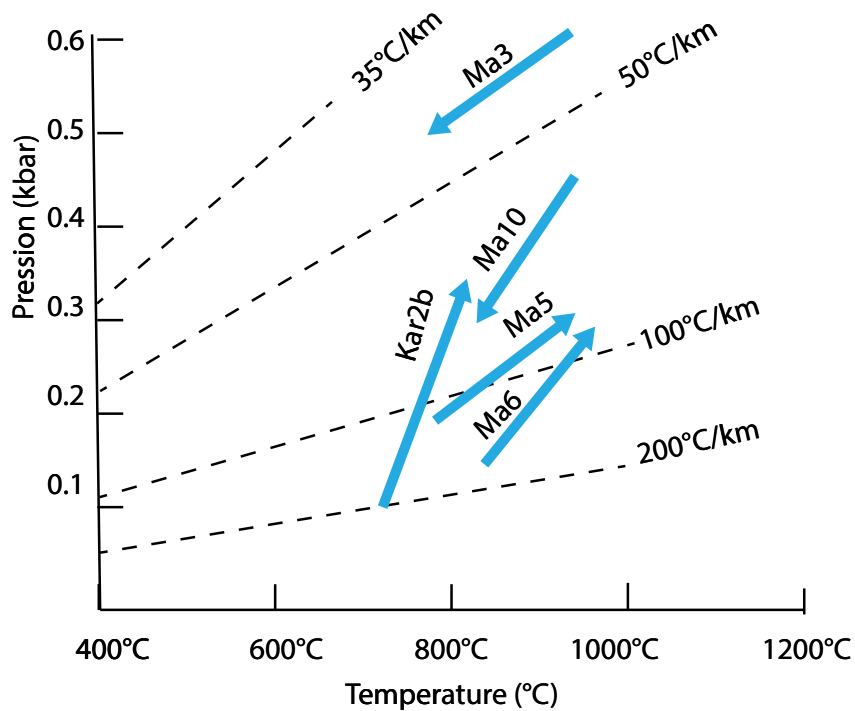


Figure 3. Summary of P-T evolution for individual xenolith resulting from thermodynamic modeling (P-T pseudosections). Reference geothermal gradients assuming lithostatic pressure

Paleomagnetic constraints on the evolution of the Variscan belt in Carboniferous-Permian times

EDEL Jean-Bernard¹
SCHULMANN Karel^{1,2}

Paleomagnetic investigations on Late Devonian – Early Carboniferous volcanic, plutonic, metamorphic and sedimentary units from central and western Variscides show that most rocks have been remagnetized in Middle-Late Carboniferous times. Three major overprint phases have affected rocks of the Armorican Massif, Central Massif, Vosges, Black-Forest, Odenwald, Spessart and the Bohemian Massif. These phases occurred after the main orogenic event responsible for the development of Variscan orogenic root system, i.e. in the interval between 330 Ma and 300 Ma. Only in two specific areas, the northern Vosges and the Central Bohemian Massif, Early Carboniferous granitoids and metamorphic rocks emplaced in the time range 340-330 Ma rocks have escaped the late overprinting phases thereby allowing deciphering the tectonic evolution during the Carboniferous convergence and subsequent tectonic evolution of assembled system. These paleomagnetic results are in favour of the following evolution:

The northern part of the belt shows following succession of tectonic events documented both by paleomagnetism and geological analysis:

- 1) the interval of 335-330 Ma is characterized by 50° counter-clockwise rotations of the assembled Variscan collage, associated with activity of large dextral strike-slip faults (presently striking NW-SE: South Armorican, Bray, Thuringian-Bavarian, Elbe faults) ;
- 2) the interval of 330-325 Ma is marked by south-eastward tilting associated with activity of NE-SW striking normal shear zones (e.g., the Tepla-Barrandian or Central Vosges extensional collapse). Structural investigations show that this event is connected with subsurface horizontal flow in the root domain ;
- 3) clockwise rotation by about 70° of the whole belt associated with NW-SE to N-S shortening of the Variscan belt in between converging Gondwana and Baltica during

Middle-Late Carboniferous. This event is manifested by development of wide sub-vertical deformation zones and important anatectic-magmatic event. Associated major and pervasive magnetic overprinting phase affects the whole N-S oriented belt in the Late Carboniferous ;

- 4) finally, the time interval between 315-290 Ma is characterized by a new phase of clockwise rotation by ~45° associated with important magmatic and tectonic activity along marginal parts of orogenic system. During and after docking of the Rhenohercynian series onto the London-Brabant block, northern Europe and Baltica participate to this clockwise rotation until Mid-Permian.

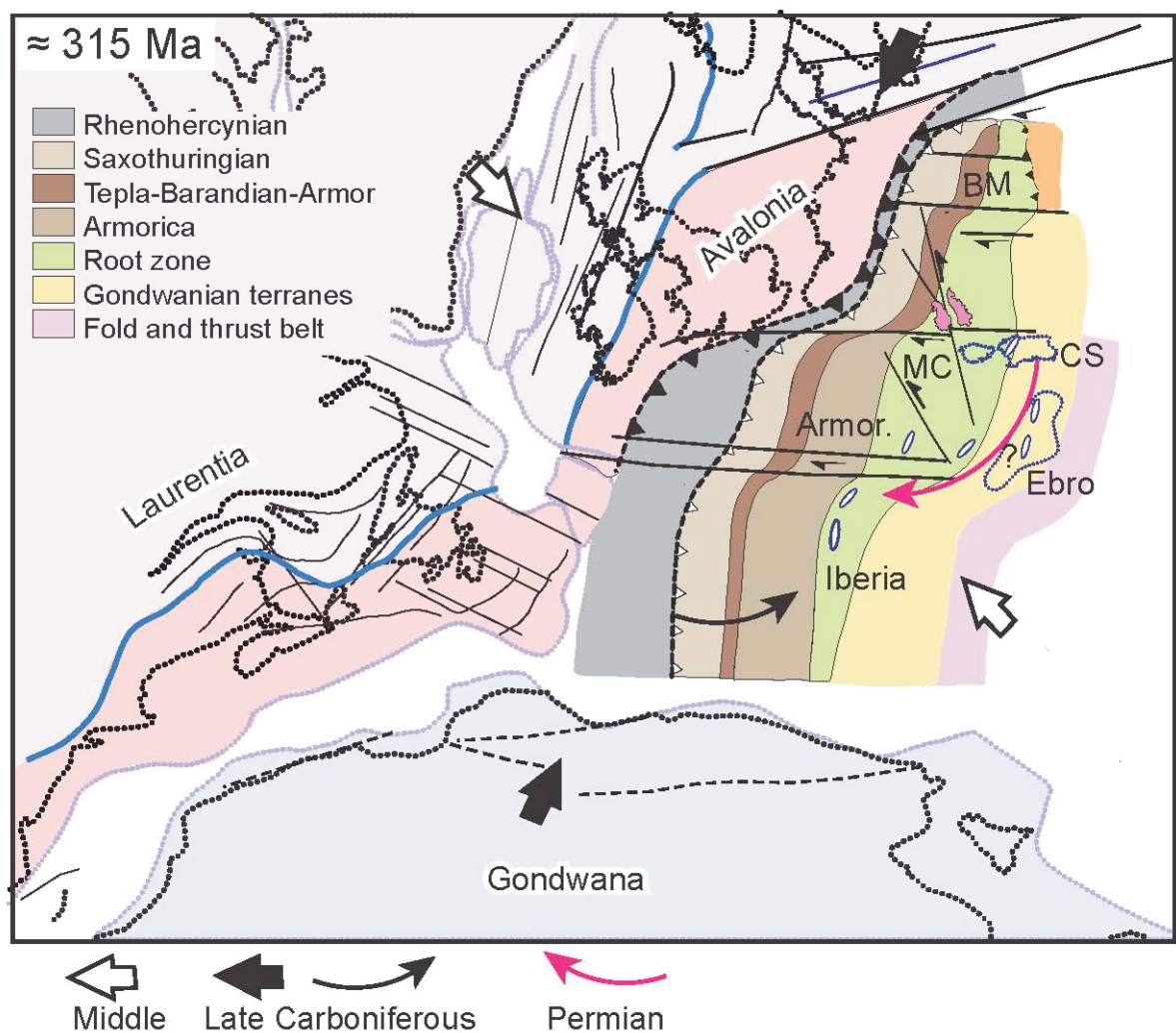
The southern Variscan belt shows different evolution compared to north:

After collision of the northern Variscan belt with Avalonia, dextral wrenching and rotations continue in the southern part of the belt, up to the Late Permian – Early Triassic. Paleomagnetic studies of Late Carboniferous - Permian dykes, volcanic flows and granitoids show a succession of two clockwise rotations:

- 1) the first 90° rotation that affects the Maures-Corsica-Sardinia-Calabria block takes place in the time range 300-280 Ma. This period is consistent with a 90° switch in the direction of shortening revealed by structural geology. In the time range 280-260 Ma, the microcontinent as well as the adjacent Ebro block in Spain continue to rotate clockwise by ~35° around the southern Massif Central. This Late Carboniferous - Permian-Triassic clockwise rotation is associated with closure of northern limb of the Iberian arc contemporaneously with the counterclockwise rotation of the southern limb of the Iberian orocline dated at the Late Carboniferous (Weil *et al.*, 2013) ;
- 2) a late phase of additional ~35° rotation is associated with alkaline magmatism and probably marks the onset of the Neothetys basin opening further east.

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Situation after the Middle Carboniferous clockwise rotation of the whole Variscan Belt and docking of the northern part to Avalonia, and before the Late Carboniferous - Permian counterclockwise (W. and S. Iberia: black arrow) and clockwise (Maures - Corsica - Sardinia - Ebro block: red arrow) rotations that led to the Ibero-Armorican Arc.

The Ibero-Armorican Belt: an evolving island-arc along northern Gondwana between ca. 650 and 480 Ma

EGUILUZ L.

MARTÍNEZ-TORRES L.M., SARRIONADÍA F., CARRACEDO M., GIL-IBARGUCHI J.I.

During the Ediacaran and Early Cambrian (ca. 630–480 Ma) a geodynamic setting of lithospheric convergence was established along the Northern margin of Gondwana with the result of the development of several island-arcs. The South-Iberian Massif was located at that time near the current edge of North Africa and close to the Armorican Massif, but rotated ca. 180° and further to the east of its present position. This arrangement defined a linear Ibero-Armorican Belt (IAB) which accounts for straightforward correlations between these two massifs, as is briefly described below.

The infant volcanic-arc (645–620 Ma)

This stage initiated over a low-angle subduction slab dipping towards the south and dyachronous as a consequence of strong left lateral kinematics. This subduction developed under an oceanic crust (Ossa-Morena) or a thinned continental crust with fragments of West African Craton (Armorica). The trough was located 300–400 km from the active volcanic-arc as reflect by distal marine deposits of the phtanitic "Briovérien" (Armorica) and the Montemolín Succession (Ossa-Morena). The fore-arc was integrated by E-MORB and N-MORB type basalts.

Mature volcanic-arc (580–575 Ma)

During this stage, high volumes of volcanic and plutonic rocks were generated forming discrete massifs in both zones, e.g. Mérida, Palomas, Valle de la Serena and others in Ossa-Morena, and For the Latte, St. Quay, in Armorica. An increase in the dipping angle of the subducting slab led to a deformation and metamorphic stage dated at ca. 555 Ma in Ossa-Morena and 570–560 Ma in St. Briec. Denudation of this volcanic-arc filled with detritic sediments the back-arc basins accounting for the Schist and Greywacque Complex of Iberia and the "Briovérien" of reworked phtanites in Armorica, as well as the intra-arc basins with the Binic and Embalse de Alange formations.

The late volcanic-arc (550–520 Ma)

Further increase in the dipping angle of the subducting slab was at the origin of a magmatic front close to the trough. This is reflected in Ossa-Morena by a number of intrusives (Ahillones, Mosquil, etc.) and volcano-

sedimentary sucssions like the Malcocinado Formation. Similar materials in Armorica are found in the English Channel units. Thickening and subsequent collapse of the volcanic-arc resulted in anatectic cores, like Mina Afortunada, Monesterio and Sardoal in Iberia, or the St. Malo in Armorica.

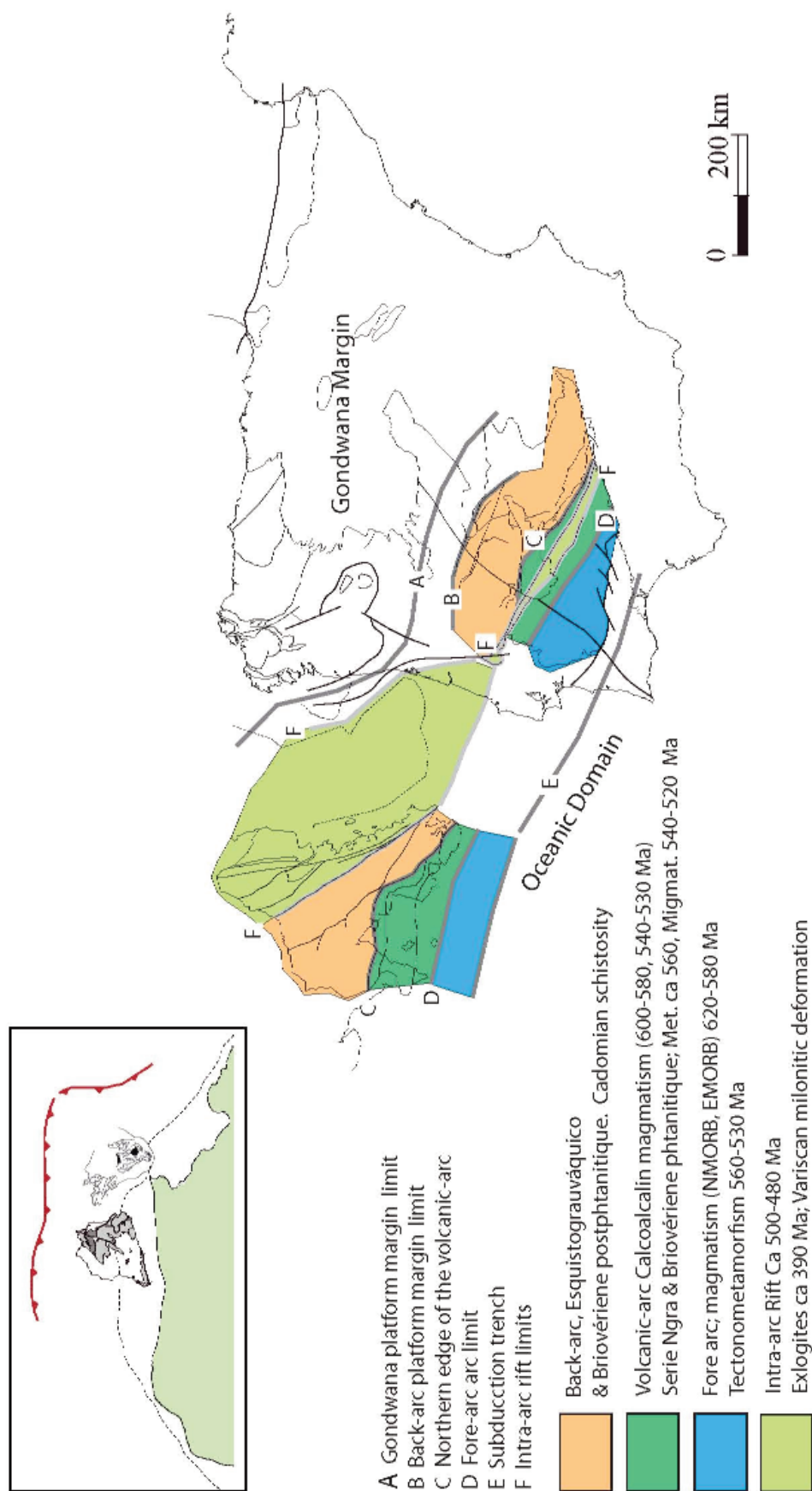
The intra-arc rifting (ca. 520–480 Ma)

A restricted Lower Cambrian sucssion is unconformably deposited onto the volcanic-arc intrusives and covered by the Armorican quartzite in both regions. Likewise, a detritic-carbonate sequence with rhyolites (Bodonal-Cala and Jabugo porphyroids) at the base dated at ca. 514 Ma is found elsewhere over the arc units while post-arc biotite and cordierite granitoids were emplaced during a long time span (from ca. 540 Ma in Brittany to ca. 490 Ma in Central Iberia) at the edge of back-arc basins.

Steeping of the subducting slab through the Middle Cambrian established an oblique intra-arc rift setting. This involved the thinning of the fore-arc region and formation of a deep trough with mafic volcanics as typified by the materials found along the Badajoz-Córdoba Blastomylonitic Corridor and equivalents in central and southern Ossa-Morena. Units related to this episode locate near the edge of the back-arc basin in Portuguese realms, whereas in Armorica occur within the back-arc basin and coincide with the South-Armorican Shear Zone (SASZ) at the border. A characterisc of this event was the emplacement of alkaline to peralkaline magmas (e.g. Castillo) along the Porto-Badajoz-Córdoba and South-Armorican Shear regions, and of intra-continental rift-related basic rocks with MORB affinity that attest to, at most, limited development of oceanic crust.

The margins of the back-arc basin platform (Lower Alcludian-Upper Brioverian) were the set for a carbonate sequence with *cloudina*, whose collapse generated olistostromes (Fuentes Formation), and for the basal shales of the Lower Cambrian (Pusa Formation) in Iberia. These materials filled sedimentary depressions located among platforms of Gondwana and the volcanic-arc realm. Possible correlatives are the limestones of St. Thuria

(Central Armorica) where the lower section exhibits an Upper Ediacaran syn-schistosity deformation.



The Ibero-Armorican Belt: an evolving island-arc along northern Gondwana between ca. 650 and 480 Ma

Variscan evolution of the Ibero-Armorican Belt

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SARRIONADÍA F.¹, MARTÍNEZ-TORRES L.M.¹, CARRACEDO M.², GIL-IBARGUCHI J.I.²

The Ibero-Armorican Belt started as an island-arc close to North Africa during Ediacaran times. The Iberian plate was at that moment rotated almost 180° with respect to the present position while the Armorican Massif was located nearby towards the east. During Middle Cambrian–Lower Ordovician an intra-arc rift setting was established oblique to the volcanic-arc trend. This resulted in a deep trough of variable width that prevented the deposition of Lower Ordovician transgressive detritic materials in northernmost areas, that is, in currently central and southern domains of the Ossa-Morena Zone (OMZ) of the Iberian Massif. The trough reached a maximum width between the Armorican and the southern Iberian Massif. This geodynamic setting extended until Late Silurian.

During the Devonian (ca. 380–400 Ma) a new subduction process started in the northern margin of the rift-related basin developing an incipient volcanic-arc and concomitant metamorphism. In this new geodynamic setting the following elements can be identified:

1. the northern margin of the rift area, which includes: the Cadomian volcanic-arc, rift-related alkaline rocks (orthogneisses), the Cambrian cover and thin slices of Devonian arc-related volcanics;
2. the rift axial zone, mostly constituted by clastic sediments interbedded with alkali mafic-felsic rocks generated during the main magmatic events.

The facing of structures related to this process is consistent with that of the oldest thrusts in the West Asturian Leonese and Cantabrian Zones of the Iberian Massif.

Rapid anticlockwise rotation of the Iberian plate starting in the upper Devonian allowed for the obduction of a large fragment of subducted crust onto the northeastern edge of the plate (remnants of which are the high pressure-units of the NW allochthonous complexes). Displacement trends were towards the current east, coincident with the emplacement of the westernmost nappes in the northern branch of the Iberian Massif. The eastwards displacement

of the arc edge rocks (e.g. volcanics and orthogneisses of the Narcea antiform) and subducted units exceeded 300 km. In the Armorican Massif the compressive regime with dextral components of a rift branch promoted the stacking of the subducted slices in the South-Armorican domain, as well as the displacement towards the north of the Léon Domain. A similar evolution is recorded in the French Massif Central. The southern Iberian Massif was subjected meanwhile to an intense left transcurrent kinematics.

The collision of Laurussia with the NW edge of the Iberian plate would lead to the N–S compression within the Ibero-Armorican arc and the collision of the South-Portuguese against the OMZ, thus completing the Variscan structure. Among the major correlation examples of allochthonous units from NW Iberia with Cadomian arc units stand out the following:

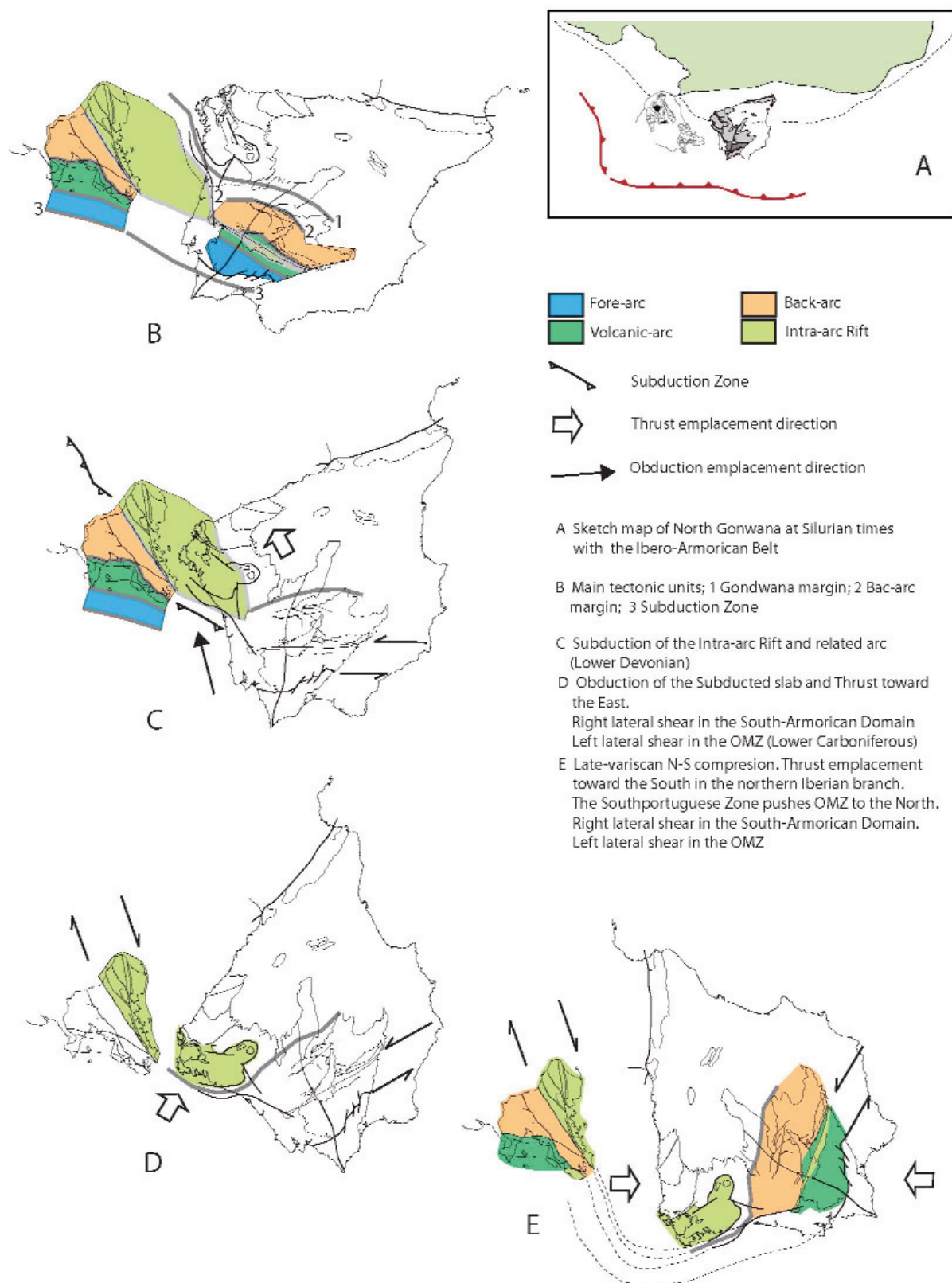
- a) the Basal Unit materials of Malpica-Tui and the like are correlative with the Badajoz-Córdoba Blastomylonitic Corridor rocks of the OMZ, including the eclogitic metamorphism;
- b) the Ophiolitic Units correspond to mafic rocks related with the rifting process, and are equivalent to central and southern OMZ mafic volcanics and gabbros dated at ca. 500 Ma;
- c) quartz-feldspathic (Chimparra) gneisses at Cabo Ortegal and equivalent units are correlative with Cadomian anatectic domes (ca. 550–530 Ma) with a Variscan high-pressure overprint (ca. 390 Ma);
- d) the high-pressure and high-temperature (granulites, eclogites) and Uppermost lower grade units correspond with the subducted volcanic-arc (ca. 390 Ma).

Despite this tectonic complexity, the correlation of all the allochthonous units with autochthonous equivalents suggests a near origin for the protoliths of the allochthonous. In consequence, it is not necessary to search for oceans and/or consumed arcs to explain the genesis of this segment of the Cadomian-Variscan chain.

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VARISCAN EVOLUTION OF THE IBERO-ARMORICAN ARC



Variscan orogeny in the Eastern Variscan Branch: New structural and geochronological insights from Corsica and surrounding areas

FAURE Michel¹

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The E. Variscan branch develops from the Bohemia to the Mediterranean sea through Alpine basement, Maures, Corsica, Sardinia, and several fragments dispersed in the Mediterranean area (Calabria, Kabylia, Betics). Due to the intense Mesozoic and Cenozoic events, the E. Variscan branch remains poorly understood. In Western Corsica (Figure), remnants of prebatholithic lithological and metamorphic assemblages are preserved as km-scale septa enclosed in Lower Carboniferous to Early Permian plutons. Two groups of septa are recognized: 1) the Argentella and Agriates-Tenda fragments correspond to Neoproterozoic rocks deformed and metamorphosed during the Cadomian orogeny, 2) the Zicavo, Porto Vecchio, Solenzara- Fautea, Belgodère, Topiti, and Vignola septa consist of Variscan migmatites and metamorphic rocks. The lithological content and the ductile deformation events for each septum are presented. In the Zicavo, Porto Vecchio, and Topiti septa, a top-to-the-SW ductile shearing (D1 event) coeval with an amphibolite facies metamorphism, is responsible for crustal thickening at ca 360 Ma. This main event was preceded by eclogite- and granulite-facies metamorphic rocks preserved as restites within migmatites dated at ca 345 Ma. A top-to-the-SE ductile shearing (D2 event), coeval with the crustal melting accommodated the exhumation of the D1 event. In contrast, the Belgodère segment is peculiar as it corresponds to a migmatitic antiform overturned to the East. However, retrogressed high-pressure rocks (eclogites and granulites) are also recognized.

High-precision SIMS U-Pb zircon age determinations were conducted on migmatites and Mg-K magmatic suites.

Zircons from leucosomes of migmatites from Vignola, Fautea, and Belgodère yield consistent crystallization ages of ca. 345 Ma. Four Mg-K granitoid rocks and one monzogabbro enclave from the Calvi-Ile Rousse pluton of NW Corsica yield indistinguishable U-Pb zircon ages of ca. 330 Ma. These new SIMS zircon U-Pb dating results indicate that the regional crustal anatexis under amphibolite-facies condition occurred synchronously at ca. 345 Ma throughout the Corsican Variscan segment.

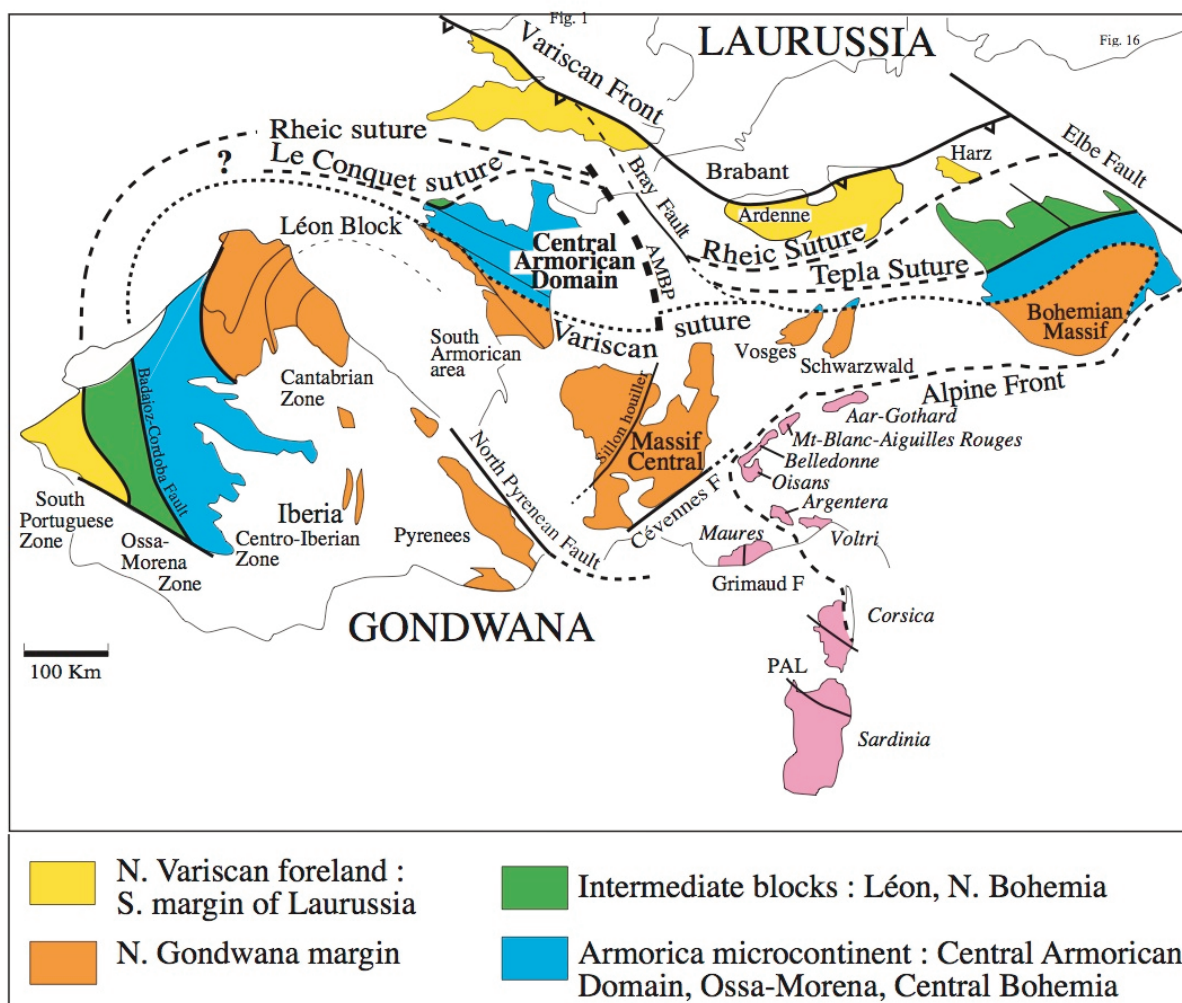
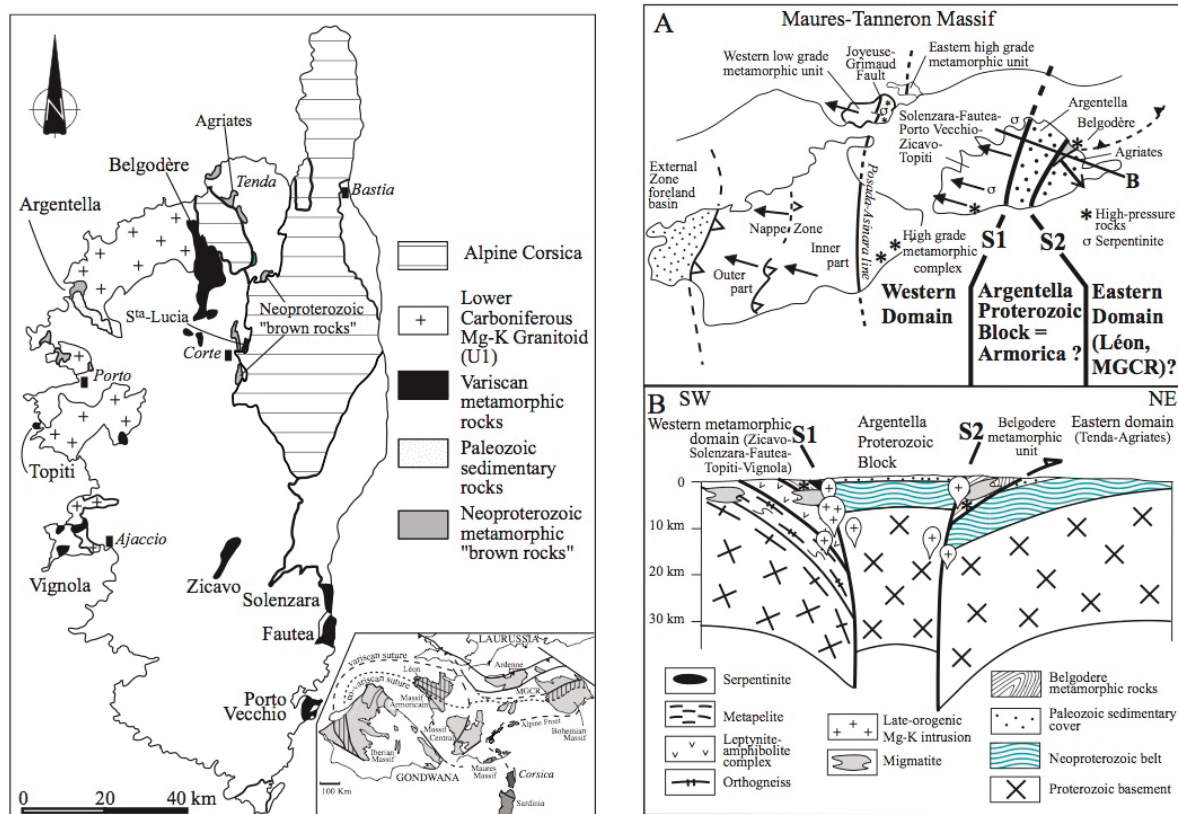
The pre-Permian fragments of Variscan Corsica are arranged in four NW-SE striking stripes that define a SW-NE zoning with: i) a Western domain in Topiti, Vignola, Zicavo, Porto Vecchio, and Solenzara-Fautea, ii) a Neoproterozoic basement with its unconformable Early Paleozoic sedimentary cover in Argentella, iii) an Eastern metamorphic domain in Belgodère, iv) another Neoproterozoic basement with its Upper Paleozoic sedimentary cover in Agriates-Tenda. The Argentella basement is separated from the Western and Eastern domains by two sutures: S1 and S2. The Variscan Corsica represents the eastern part of the Sardinia-Corsica-Maures segment (Figure). The comparison of this segment with other Variscan domains allows us to propose some possible correlations with the Variscan domains exposed in the Alpine Crystalline Massifs of Argentera, Pelvoux, Belledonne. At the scale of the entire Variscan orogen, we argue that the Western domain, Argentella, Belgodère, and Agriates-Tenda domains can be correlated with the southern Variscan belt exposed in French Massif Central-southern Massif Armorica, Armorica microblock, Léon block (ie Saxothuringian zone), respectively.

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A review of Variscan metamorphism and deformation in northern Sardinia, Italy

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Structural, petrological and geochronological data from central and NE Sardinia allow to unravel the role of the Corsica-Sardinia microplate in the tectonic puzzle of the southern Variscan Belt. Three main structural zones are distinguished from SW to NE in the Sardinian branch of the Variscan belt: 1) in SW Sardinia a foreland made up of very low to low grade metasedimentary sequences; 2) a SW-vergent nappe pile, consisting of low-grade metasedimentary rocks including calc-alkaline Middle Ordovician volcanic sequences; 3) a Low- to Medium-Grade Metamorphic Complex (L-MGMC) made up of micaschists and paragneisses with embedded metabasites; 4) a polyphased High Grade Metamorphic Complex (HGMC) consisting of migmatites (Cruciani *et al.*, 2001, Massonne *et al.*, 2013) and amphibolites still preserving eclogite and/or granulite assemblages (Franceschelli *et al.*, 2002). The last two metamorphic complexes forming the so called Inner Zone of the Variscan Sardinia show a gradual increase of the metamorphic grade from biotite to Al-silicate (sillimanite, rare kyanite) + K-feldspar Zone. Five deformation phases have been identified. The D1 deformation is recognizable in the southern part of the Inner Zone and is gradually transposed by the D2 foliation. The last deformations D3, D4, D5 are locally recognizable but not ubiquitous as the D1 and D2 deformations. A phase of HP metamorphism (Cruciani *et al.*, 2013) coeval to the D1 deformation is testified by metabasites and schists and is related to the collision produced by the northward subduction of the continental crust being part of the north- to peri-Gondwanian terranes during Lower Paleozoic. The HP phase was followed by a

Barrovian-type metamorphism. The final late Variscan exhumation of the HGMC generated the stacking of the metamorphic sequences that gave origin to the nappe pile observed in central-northern Sardinia. The stacking of the metamorphic sequences was activated by the NW-SE trending top-to-the S, SW dipping shear zones and faults showing a major dip-slip component of movement contemporaneous to the late stage of deformation. In the final stages a dextral transpressional deformation affected both the HGMC and the L-MGMC enhancing their exhumation. The final extensional tectonic regime was characterized by the local occurrence of HT-LP metamorphism. During Middle Carboniferous-Permian post-collisional stages of the Variscan Orogeny intrusion of large igneous suites of the Corsica-Sardinia batholith were coeval with the last deformation phases and metamorphic events of the Sardinian Variscan branch.

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Variscan Oceans: how many, where and when?

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Recent models for the plate tectonic evolution of the Variscides propose one main ocean (the Rheic), while oceanic separations between members of the Armorican Terrane Assemblage (ATA) and the ATA and Gondwana are considered insignificant (e.g., 1, 2). Also, closure of the Rheic ocean is held responsible for the origin of notional arc and back arc elements still in Carboniferous time (3). However, palaeogeographic simplicity is not a scientific argument and complicated scenarios involving microcontinents are frequent in Earth's history as well as today (Alps, Cimmerian terranes, East-Africa and Indian ocean, Greenland and Jan Mayen...).

Published evidence (4, with refs.) clearly reveals that the Rheic ocean (defined as the separation between Avalonia and the ATA) closed already in Emsian time. The suture is situated within the Northern Phyllite Zone of the central European Variscides, between a Silurian magmatic arc and ATA-related Ordovician metasediments ("Bierstadt Phyllites" of the S-Taunus, Wippra Zone of the southern Harz Mts.). The Rheno-Hercynian (RH) narrow ocean opened in Emsian time, probably by SE-ward subduction of the Rheic mid-ocean ridge. During closure of the RH ocean, ATA-rocks (whose metamorphosed equivalents are now contained in the NPZ) were carried over the RH foreland, where they are now found in tectonic mélange zones at the base of the Gießen-Harz allochthons.

In other parts of the Variscides (e.g., Iberia), opening of the RH ocean may have exactly retraced the Rheic suture, so that RH processes are erroneously attributed to the Rheic (5).

With the Rheic closed in Emsian time, middle Devonian through to early Carboniferous orogenic processes must relate to the closure of narrow belts with thinned lithosphere (comparable with the Alpine oceans), which dictated the sites of subduction/collision, such as the Saxo-Thuringian and Galicia-Moldanubian basins. If one bears in mind the close biogeogeographic connections between the members of the ATA/Gondwana assemblage (6) and also restores the involved microcontinents to their pre-tectonic width (7, 8), no space is left for mature oceans with formation of arc and back arc elements. Geochemical fingerprints frequently used to detect subduction-related magmatism are - at best - ambiguous, because they may well result from recycling of Andean-type Cadomian crust and mantle lithosphere in a high-T environment (9, 10) caused by incipient Tethys rifting (9, 11).

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Petro-structural evolution of the Belledonne massif: Implications for the Variscan orogenic evolution

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The Variscan belt represents the pre-Permian basement of central and western Europe. Extending from Iberia to Bohemia through Massif Armoricain, Massif Central, Vosges, and Schwarzwald, the western part of Variscan orogen is relatively well understood. In contrast, the Southeast Variscan Branch, developing from Bohemia to Sicilia through the Alpine basement, remains poorly studied, and thus the relationships between the Meridional Variscan branch and the other parts of the belt remain hypothetical.

In order, to decipher the Variscan orogenic evolution of the Alpine basement, we performed an extensive structural, petrological, and geochronological study along a W-E cross section in the Romanche valley, throughout the Belledonne crystalline massif. From West to East, the following litho-tectonic units are recognized. 1) The West Belledonne micaschist unit (série satinée) is formed by a Neoproterozoic weakly metamorphosed alternation of sandstone and mudstones. 2) The Chamrousse ophiolite, of early Ordovician age, should probably be subdivided into several thrust sheets as the ultramafic rocks tectonically overlie the mafic ones. 3) A volcanic-sedimentary unit (or Rioupéroux-Livet Unit: RLU) consists of an alternation of several rock types, mafic plutonic rocks, volcanoclastic rocks, plagiogranites, metapelites and migmatites. 4) A terrigenous sedimentary series with sandstone, siltstone, and metaconglomerates (gneiss amygdalaires). Lastly, a sandstone-conglomerate, series with felsic lava (keratophyres), called the Taillefer series, of probable

Viséan age, unconformably overlies the volcanic-sedimentary RLU unit. In spite of Alpine deformation that may locally induce ductile fabrics superimposed on the Variscan ones, and change the initial geometry, the bulk Variscan architecture is a stack of E-directed synmetamorphic nappes built-up through two main events.

The first one, D1, is responsible for the crustal thickening accommodated by the Eastward emplacement of the Chamrousse ophiolitic complex upon the RLU, itself overthrust upon the terrigenous unit 5. Along the eastward overthrust of the RLU metapelites upon unit 5, the Allemont shear zone with metatexites develops. The D1 event is coeval with a MP-HT (ca. 7Kbar, 650°C) metamorphism represented by kyanite-staurolite-garnet assemblage in metapelite. D1 occurred around 345-340 Ma, as zircons from a RLU plagiogranite yield ca. 352 Ma magmatic age, and it is post dated by the 335-325 Ma Sept-Laux pluton. Furthermore, the Allemont shear zone includes garnet amphibolite boudins that experienced an early eclogite-facies metamorphism.

The D2 event that involves the Taillefer unit, is characterized by NW-SE trending upright to NE-verging synfolial folds. D2 folding is pervasively developed in all litho-tectonic units.

These new data are replaced in a preliminary geodynamic model, and tentatively correlated with adjacent Variscan massifs.

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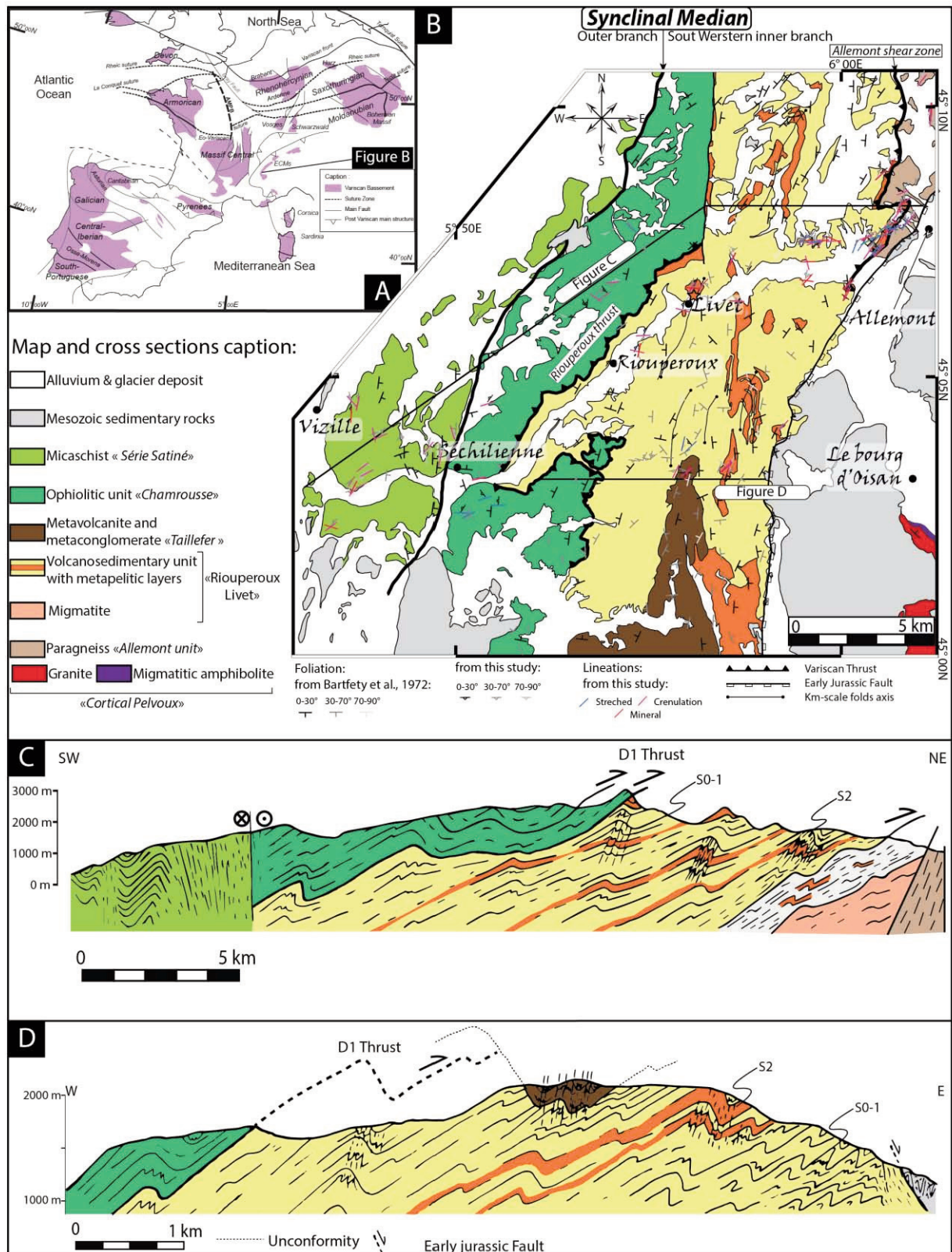


Fig. 1.- A: Location of the Alpine External Crystalline Massifs within the Variscan belt. B: Geological Map of the Southwestern part of the Belledonne massif. C: SW-NE cross section through Belledonne massif. D: W-E cross section through the Taillefer unit. The two cross sections are located on figure B.

Geothermobarometry of very low-grade Devonian metabasalts of the Elbingerode Complex (Harz Mountains, Germany) - implications of chlorite and phengite composition

FRIEDEL C.-H.

The Devonian metabasalts of the Elbingerode Complex (EC) in the Harz Mountains (eastern Rhenohercynian Belt) were affected by Variscan very low to low-grade (upper anchizonal) regional metamorphism. In the metabasalts a non-diagnostic metamorphic mineral assemblage occurs, consisting of chlorite-phengite-albite \pm quartz, calcite, sphene (titanite), while Ca-silicate index minerals are lacking. Therefore, the estimated P-T conditions of regional metamorphism in the EC are essentially based on the composition of the abundant syntectonic grown metamorphic mineral phases Al-rich chlorite and Si-rich K white mica (phengite). Both Fe-Mg phyllosilicates reveal a significant compositional spread controlled by the bulk rock chemistry. Nevertheless, local chemical equilibrium is suggested by the regular partitioning of iron and magnesium between coexisting chlorite and white mica.

The P-T conditions were deduced from several methods including empirical and thermodynamic approaches of chlorite geothermometry, phengite geobarometry and the results of multi-equilibrium P-T calculations for the chlorite-phengite-quartz-H₂O assemblage. This multi-methodological approach yields peak metamorphic

conditions of 4-5 kbar \pm 1kbar at 280 °C \pm 20 °C. This data were proved by P-T calculations using the diagnostic mineral assemblage prehnite-pumpellyite-actinolite in Devonian volcanic rocks outside the EC (300 °C, 4.5 kbar, Theye & Friedel 2012). The obtained P-T conditions also fit well with metamorphic data obtained from pelitic rocks (Illite crystallinity, coal rank, b0 parameter). The good agreement of the constrained P-T conditions underlines the improved possibilities of obtaining reliable P-T data on basis of chlorite-phengite local equilibria in the very low- to low-grade metamorphic realm.

The P-T conditions indicate a medium-pressure style of metamorphism and hence a tectonic burial in the central part of the eastern Rhenohercynian Belt much deeper than previously assumed. Such pressure conditions are commonly thought to be restricted to the Northern Phyllite Zone at the southeastern boundary of the Rhenohercynian Belt.

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Sedimentary vs. tectonic mélanges - a case study from the Harz Mountains (eastern Rhenohercynian Belt)

FRIEDEL C.-H.¹

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The origin of mélanges can be difficult to determine, especially if the whole strata are tectonically overprinted, which is the case in e.g. the Harz Mountains (Harz). The Harz is an uplifted section of the Rhenohercynian Belt in northern Germany and consists of a pile of autoch- and allochthonous units (zones) composed mainly of pelagic siliciclastic rock suites of Silurian to upper Lower Carboniferous age and stacked under very low- grade conditions in depths of up to about 15 km.

For the past fifty years, large parts of the Harz have been regarded to consist of sedimentary mélanges (olistostromes, e.g. Reichstein 1965, Lutzens 1972, 1991). The olistostrome model was associated with the assumption that sliding of coherent nappe units occurred contemporaneously with the mass flow processes. Due to the strong Variscan deformation (foliation) of the rocks, the mélanges have been interpreted as deformed olistostromes. The criteria for a sedimentary origin of the mélanges were based on the characteristic block-in-matrix fabric of the rocks (bimrocks) and the composition of the blocks. However, lateral extension and age of olistostromes remained a matter of debate (e.g. lower or upper Lower Carboniferous, Lutzens 1991). Despite this controversy, the olistostrome model has been widely accepted. Only a few authors assumed a pure tectonic origin of the mélanges (e.g. Huckriede *et al.*, 2004).

Based on recent fabric studies of outcrops and drilling cores at different scales, it can be shown that (a) nearly all stratigraphic units (Silurian up to the upper Lower Carboniferous) exhibit block-in-matrix fabrics, and (b) the fabric of the bimrocks mainly developed during Variscan fold-and-thrust tectonics (*cf.* Friedel & Zweig 2013). To distinguish tectonic fragmentation from a possible sedimentary, mass-flow related stratal disruption, relationships between block fragmentation and tectonic foliation fabrics were established. Structural pattern

indicative for a tectonic origin are e.g. boudinage associated with strong mineralization, mylonitization, shearing and transposition of folded layers along the main foliation, all of them developed in a brittle-ductile deformation regime without indication of soft rock deformation or sliding.

Former biostratigraphic data and a reevaluation of the composition of the blocks show that large amounts of the former olistostromes consist of broken formation, *i.e.* bimrocks which contain only native (intraformational) blocks. Also mixing of blocks of different lithology and age (intra- and extraformational blocks) locally occur, but is commonly limited to the intensely sheared boundaries between different units. Furthermore, even in well investigated drillings the expected basinal sediments of Lower Carboniferous age could not be detected in direct relationship to the bimrock strata, only the Devonian host rocks of broken formations have been dated repeatedly (*cf.* Borsdorf *et al.*, 1992).

Our results show that probably most of the formerly regarded olistostromes are of tectonic origin (tectonic mélanges). Tectonic mélanges and broken formation are parts of large scale shear zones which developed during the underplating of the Rhenohercynian beneath the Saxothuringian crust at the final stage of the Variscan collisional tectonics.

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When a partially molten orthogneiss meets a syntectonic granite along the Northern flank of the Canigou massif, Axial Zone of the Pyrenees

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VANDERHAEGHE Olivier

In this contribution, we compare the structural record of orthogneisses and syntectonic granites exposed along the northern flank of the Canigou massif, in eastern part of the Axial Zone of the Pyrenees, in order to identify the kinematics and the PT conditions of variscan deformation. Special attention is devoted to the relationships between deformation and melt migration/segregation.

Syntectonic granites and orthogneisses have similar petrological-geochemical characteristics with facies ranging from monzogranite to leucogranite and a calc-alkaline affinity. The difference between orthogneisses and granites is evidenced (i) in the field by the fact that orthogneisses are present as enclaves in granites and display a foliation cross-cut by granitic veins, (ii) by U-Pb ages obtained on zircon indicating an ordovician age for orthogneisses and a variscan age for granites. Orthogneiss and syntectonic granites also show a similar microscopic characteristics with submagmatic deformation textures partially overprinted by intracrystalline deformation grading from protomylonitic to ultramylonitic and locally into cataclasite. Submagmatic textures are characterized by K-feldspar phenocrysts included in a mica-rich matrix associated with feldspar and quartz.

At low-strain, intracrystalline plastic deformation is expressed by undulatory extinction of K-feldspar porphyroclasts and by the development of quartz mono- to polycrystalline lenses with a prominent shape

preferred orientation (SPO) parallel to the magmatic foliation. Quartz grains commonly show chessboard texture and subgrain boundaries. Bulging of quartz-quartz grain boundaries is dominant, (Fig. 1A, 1E). Increasing intracrystalline deformation is marked by a core and mantle microstructure with strain-free subgrains surrounding K-feldspar porphyroclasts and relictual quartz grains with undulatory extinction. Feldspar porphyroclasts are cross-cut by quartz-feldspar veins indicating that deformation occurred in the presence of melt, (Fig. 1B, 1C) Myrmekites, localized along the boundary of K-feldspar porphyroclasts, suggest that K-feldspar have been reacting with the melt fraction, (Fig. 1F, 1G). Strain localization is evidenced by a grain-size reduction delineating a mylonitic fabric characterized by a polygonal foam texture in the quartz-feldspar matrix alternating with mica-rich layers. Rare rounded K-feldspar porphyroclasts are wrapped into this mylonitic foliation, (Fig. 1D, 1H). Kinematic criteria are consistent with a dominant top-to-the-north sense of shear.

Textures and microstructures of orthogneisses and syntectonic granites exposed along the northern flank of the Canigou massif are consistent with progressive deformation of orthogneisses in the presence of melt coeval with the progressive intrusion and crystallization of granitic veins forming a sills-and-dikes network feeding syntectonic plutons at higher structural level.

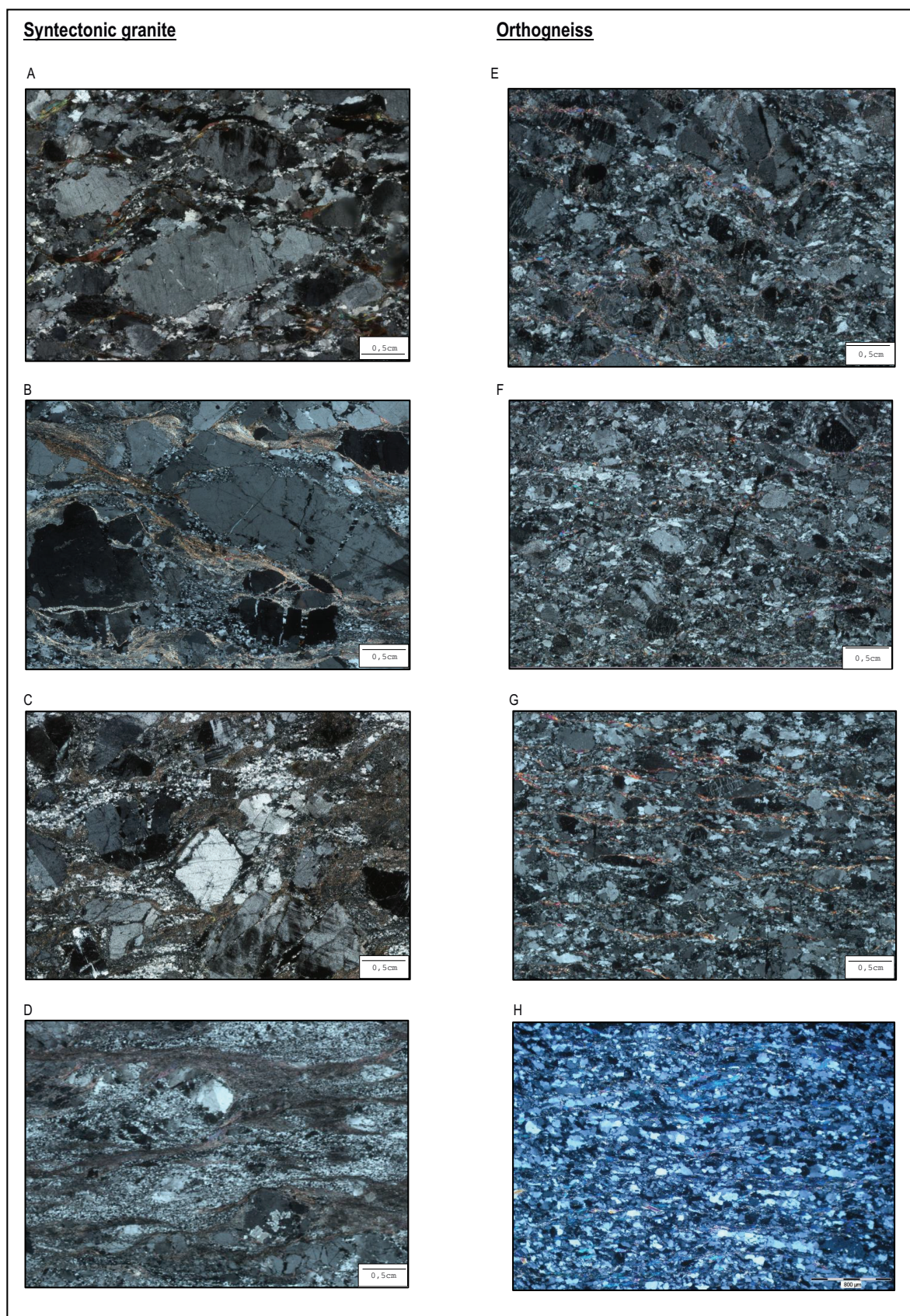


Fig. 1.- Intracrystalline deformation grading of syntectonic granites and an orthogneisses, optical microscope for the sample H, and thin sections scanned for samples A-B-C-D-E-F-G . Samples A and E represents a low strain. Quartz grains show subgrain boundary pattern and bulging process. Increase intracrystalline deformation is evidenced with the samples B-C-F-G. K-feldspar porphyroclasts are fractured by veins filled with quartz and feldspar, and relictual quartz grains with undulatory extinction. Sample D is characterized by grain size reduction and some Kfs porphyroclast surrounded by braided mica layers. Sample H shows a mylonitic texture, feldspar and quartz are recrystallize.

Ore deposits around the Ibero-Armorican arc and their relations to the Variscan orogeny

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The Variscan orogeny is mainly responsible for the present-day structuration of the so-called Ibero-Armorican arc (IAa). During this orogeny, large volumes of rocks were variously deformed, metamorphosed, affected by partial melting events, intruded by several magmatic intrusions or percolated by huge amounts of hydrothermal fluids. Most of these events are generally highly favourable to the generation of large ore deposits. Conversely, there is a lack of large ore deposits related to the Variscan orogeny in the IAa. Nevertheless, medium- to small-size ore resources typical of a collision-type orogenic belt - i.e. Sn, W, Nb, Ta, Li, Au, U, Mo, Cu - still exist on both sides of the IAa. Despite this common metal-signature encountered in the IAa, the relative proportion of each metal concentration and type of ore deposit is strongly different on each side of the arc. Indeed, NW Iberia is characterised by numerous granite-related Sn-W deposits, Sn-Li-Ta-Nb pegmatites and orogenic gold deposits whereas antimony and uranium deposits appear most represented in the Armorican Massif. An explanation could be the huge difference of Variscan thickened domains that are at present significantly more exposed in NW Iberia compared to the Armorican Massif. However, most of above mentioned intrusion or fluid-related ore deposits may be formed indifferently in thickened or non-thickened parts of the orogenic belt. Then, other small or large-scale key-features may be also involved in ore formation processes. The four main steps of the Variscan orogeny s.l. - 1) Devonian subduction-arc-back-arc setting; 2) Carboniferous collision & nappe stacking; 3) late Carboniferous generalized extension followed by 4) Permian rifting - seem to be recorded by various types of ore deposits through time and space. Indeed, the northward oceanic subduction of Galicia-Massif Central ocean may be large-scale control of: i) early fluid flows in non-thickened domains responsible for the formation of Eu-monazite disseminations and early stages of scarce variscan hydrothermal base metal deposit at ca

385 Ma and ii) Formation of lower Devonian volcano-sedimentary massive sulphides. Carboniferous nappes stacking and main exhumation of the subducted continental crust may, in part, control hydrothermal cells which are responsible for the formation of Variscan base-metal deposit in the Central-Iberian & Armorican zones. The syn-convergence extension that affects the belt from ca 325 Ma is associated to the formation of numerous intrusion-related ore deposits (ca 326-315 Ma): i) Sn-W systems associated to peraluminous 2-micas leucogranites; ii) Rare-metal granites; iii) Au veins associated to Mg-K metaluminous to peraluminous granites. These deposits are emplaced both in the thickened and non-thickened parts of the arc but are frequently associated to shear zone. Following these intrusion-related ore deposits, numerous fields of rare-element pegmatites emplaced in NW Iberia between 310 and 301 Ma. Huge hydrothermal cells, probably coeval with this event, lead to formation of orogenic gold deposits spatially associated with shear zones. Several distinct hydrothermal cells may exist since antimony ore deposits, with or without gold, are also formed at the same period. Close to 300 Ma, the general extension followed by the Permian rifting is the last event of intrusion-related mineralization. Mo-porphyries and Sn-W-Cu veins systems are associated with the emplacement of late Fe-K metaluminous to peraluminous polyphased granitoid complexes from ca 300 to 280 Ma that frequently re-used Cadomian faults. This event is coeval with the formation of the world-class Sn-W-Cu mineralized district of SW England.

Clearly, different types of ore deposits are related to different ages and tectonic settings and understanding the orogenic evolution is one of the keys to a more efficient ore exploration.

The sole thrust of the Lower Allochthon to the west of the Morais Complex (Portugal): Correlation with the Lalín-Forcarei thrust in the Órdenes Complex (Spain)

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Unraveling the kinetic and deformational history of major tectonic contacts in orogens is one of the main objectives in geodynamic studies. However the existing uncertainty about whether and how tectonic fabrics reflect distinct features of the deformative flow, has maintained the controversy about interpretation of rock fabric in terms of transport direction in a number of mountain belts. Detailed structural mapping, combined with metamorphic and geochronological studies, and with rheological assumptions about flow, have proved to be a successful way to shed light on that debate (e.g. Díez Fernández and Martínez Catalán, 2012). This approach could be useful for detecting tectonic reworking of regional volumes. However, in the case of discrete recycling of fabrics in shear zones (reactivation), the quantitative analysis of microstructures has demonstrated crucial in assigning a kinetic meaning to the mineral fabric (Gómez Barreiro *et al.*, 2010; Gómez Barreiro and Martínez Catalán, 2012; Gómez Barreiro *et al.*, 2015).

A case study is presented where both quantitative analysis of tectonites and tectonometamorphic information were combined to identify the sole thrust of the Lower Allochthon to the west of the Morais Complex (Trás-os-Montes, Portugal), close to the village of Contins. A shear zone with penetrative development of mylonites and ultramylonites limits the so-called Complexo Vulcano Silicioso above and the Formação Filito-Quartzítica (Ribeiro *et al.*, 1990), which are correlated with the Lower Allochthon and Parautochthon respectively on the basis of lithological and

metamorphic criteria. Deformation conditions and kinematics (top-to-the-SE) along with the structural location supports correlation with the Lalín-Forcarei thrust in the Órdenes Complex (Galicia, Spain; Martínez Catalán *et al.*, 1996). The possibility of partial reactivation as an extensional detachment is investigated.

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Another model for the Western Europe Paleozoic Variscan evolution: questioning redundant subduction and oceans

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Understanding the causes of the opening and closure of oceanic tracts is a major ongoing endeavor in contemporary Earth Science. Ancient oceans are a key clue to unravel this evolution because they preserve the record of the different processes involved and so shed light on the causes of ocean opening and widening, and the subsequent dynamic flip towards convergence and closure. One of the best candidates for unravelling the causes involved in the birth and demise of oceans may be the Rheic Ocean (or oceans). This is one of the world's most studied ancient oceans because its closure is one of the main factors in the building of Pangea. Nevertheless, the myriad of different interpretations of its origin and evolution advocated by different working groups make it difficult to conceptualize the causes of its opening and its dynamic flip from oceanic growth to closure. Most recent interpretations rely on the effects of subduction rollback for its creation and subsequent evolution, but other explanations can also be found. In particular, the necessary subduction of the mid-ocean ridges during the evolution of both the Iapetus and Rheic oceans, that is seldom mentioned but may be a crucial factor in their evolution.

We present an alternative interpretation for the evolution of the Rheic Ocean from its opening along the northern margin of Gondwana in the Late Cambrian-Early Ordovician and the coeval onset of Iapetus Ocean closure, to the change in its dynamic regime, the opening of subsidiary peripheral oceanic basins, and its final closure in the Late Devonian. This interpretation is based on the effects of ridge subduction and the consequent coupling between the subduction zone(s) and the passive margins on the opposite side of the Rheic Ocean. This approach better explains some of the enigmas of the Rheic Ocean, such as the absence of magmatic arc related rocks in those areas where subduction zones are placed in many of the existing models proposed by different working groups and the cryptic distribution of oceanic like realms. The main arguments, among others, to build a new model are (1) the lack of detrital zircons in the northern Gondwana passive margin recording the existence of large subduction related arc edifices; (2) the widespread extension in lower to mid Devonian times in northern Gondwana and; (3) the correlation using detrital zircons between the "allochthonous" and "autochthonous" terranes in NW Iberia.

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Pervasive melt flow in the continental crust: examples from Variscan Orogeny

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Movement of a large volume of granitic melt is an important factor in the compositional differentiation of the continental crust and the presence of melt in rocks profoundly influences their rheology. Different mechanisms controlling melt migration through crust were proposed. We suggest that pervasive melt flow, analogous to reactive porous melt flow in mantle, could be possibly one of them. It is generally accepted that migration of felsic melts in continental crust starts with short distance pervasive microscopic flow into segregation veins which extract melt. However, we show that pervasive melt flow may be a regional mode of melt migration in continental crust. In such scenario, melt driven by deformation passes pervasively along grain boundaries through the whole rock volume. And the term pervasive melt flow is used for grain-scale, diffuse, porous and reactive flow of felsic silicate melt through rocks. This is effectively an open-system process that thoroughly reworks the resident rock mass. Through-flow of melt destroys pre-existing fabrics and the original chemical and isotopic nature of the protolith. Melt segregation is inefficient and protolith become isotropic granite-like, with partly preserved relics of the original, without ever containing more than a few melt percent at any time. This

mode is favored by rocks of low strength and low mechanical anisotropy, as well as homogeneous deformation and low melt pore pressure, which inhibit melt segregation.

In our view, pervasive melt migration may be a common though cryptic mechanism, capable of obliterating the original character of pre-existing rocks giving rise to isotropic granites. The fabric and geochemical nature of these granites encapsulates the complex history of hybridization. The porous flow of silicate melts in continental crust is a process which can operate over a long time and impacts on the rheology of the crust during orogens. The ideal setting for pervasive flow is a supra-solidus, isotropic terrane, undergoing melting reaction with negative volume change and homogeneous, low stress deformation. This corresponds to mid-crustal regions of pervasive melt-enhanced deformation as identified in Bohemian Massif or Vosges Mts. in Variscan orogeny which were interpreted to record orogenic-scale channel flow. Pervasive melt flow is slow and possibly sustained over millions of year, as exemplified by the Bohemian Massif where this process lasted up to 10 m.yr.

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Variscan metamorphic evolution of the Western Carpathians: Tatric and Veporic units

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The pre-Alpine basement of the Western Carpathians represents the easternmost exposure of the Variscan orogeny in Europe, which marks the collision of Laurasia with Gondwanian-affiliated terranes during the Palaeozoic. Variscan metamorphism is well documented in the crystalline complexes of the Tatric unit where Alpine recrystallization was relatively weak. Variscan structure is preserved in the Western Tatra, where a high-grade unit comprising eclogites, kyanite-bearing gneisses and migmatites has been thrust over a lower-grade mica schist unit, showing an inverted metamorphic sequence. Eclogites are mostly retrogressed to garnet amphibolites. Some of them, in the northern Veporic unit, preserve the eclogite facies assemblage garnet + omphacite + phengite + rutile which records the P-T conditions of up to 2.5 GPa and 700 °C, suggesting subduction to depths of ca. 80 km. These eclogites, together with less abundant garnet, olivine and orthopyroxene-bearing metaultramafics occur as lenses and boudins in kyanite-bearing ortho- and paragneisses derived from Cambro-Ordovician protoliths. Over the last decades, numerous geochronology studies have been applied to the crystalline rocks of the Western Carpathians, focusing principally on dating of zircon and monazite from the granite, orthogneiss and migmatite-bearing units. These studies highlighted a number of tectonothermal events establishing protolith ages and timing of magmatism; the timing of peak metamorphic conditions, however, remains elusive. The Sm/Nd dating of garnet from eclogite in the Western Tatra yields 342 Ma age, which reflects cooling rather than a high-pressure event. Eclogites show strong reequilibration at P-T conditions of 750-800 °C; 1-1.4 GPa, corresponding to high-pressure granulite facies in the kyanite stability field. This suggests that high-pressure rocks experienced high-temperature/medium pressure overprint at upper

mantle/lower crustal levels, most likely between 380 Ma and 360 Ma, deduced from age of zircon and monazite in kyanite-bearing gneisses and migmatites hosting eclogites. Finally, exhumation to mid-crustal levels and decompression-induced melting led to low-pressure metamorphism in the stability field of sillimanite and cordierite and formation of granitoid plutons. Timing of this event (360-340 Ma) is relatively well constrained. Tectonic profiles of the Western Tatra show that eclogites together with gneisses, migmatites and granites are accommodated in a hangingwall of an inverted metamorphic sequence, above the micaschists, being emplaced by ductile extrusion and mid-crustal thrusting. The $^{40}\text{Ar}/^{39}\text{Ar}$ ages of around 330-310 Ma reflect uplift of Variscan basement into shallow levels.

Present data suggest that Variscan orogenic cycle involved several metamorphic stages - from high-pressure, subduction-related metamorphism to lower-pressure thermal events, connected probably to heating from upwelling asthenosphere after delamination or break-off of subducted lithosphere. Low-pressure metamorphism was also locally related to intrusions of granitic magmas. Extension, rifting and upwelling of asthenosphere after the collapse of Variscan orogen in Permian to Triassic times caused low-pressure metamorphism in a thinned continental crust. Available geochronological data on Variscan metamorphism and granitoid magmatism indicate that the Western Carpathian basement belonged to those peri-Gondwanan terranes which collided with the Baltica-Laurasia megacontinent relatively early. Although there are basic similarities with internal parts of the Variscan orogen in Central and Western Europe, large-scale tectonic correlations are uncertain.

Evidence of E-W dextral shear zones in the Bas Draâ inlier (Western Anti Atlas, Morocco): Macro - to microtectonic arguments and geodynamic implications

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The south western part of the Anti-Atlas Variscan belt (AA), the Bas Draâ domain comprises units of 10 km thick Palaeozoic units surrounding the Precambrian basement. This area is part of the AA Palaeozoic fold belt which forms the southern orogenic front of Moroccan Variscan domain.

Our investigation on the Variscan shear zones from the studied areas utilizes a geological field data, structural analysis and microscopic textures in thin section under the petrographic microscope approaches constrain two dextral sub E-W shears.

Tiglite shear zone (Tsz), a minor Variscan tectonic zone in the eastern side of Bas Draâ inlier generates a deflection of Lower Cambrian folds NE-SW-trend to a sub-equatorial trend (N70°E). In addition, this shear zone generates a quartz vein cross cutting the Neoproterozoic volcanic rocks and Adoduounian conglomerate. In this later, the veins are

organized in “en echelon” array and form Z shape. Thus, the Tsz developed in response to brittle-ductile shear basement fault at mid-crustal level.

The Bas Draâ shear zone (BDsz) at south of Bas Draâ domain, induced structures rotation in a continuous way to a NE-SW trend becoming sub E-W. Furthermore, the BDsz gives rise to gold-bearing quartz veins. Mylonite fabric, deformation lamellae, undulose extinction and recrystallization textures are the main microscopic structures of brittle-ductile deformation developed in the main BDsz.

BDsz and Tsz correlation to analogue dextral shear zones in the Variscan outcrops in Morocco and in the peri-Atlantic belts fit well on the dextral oblique collision between Laurentia and Gondwana plate tectonic evolution.

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Tectono-Metamorphic Evolution of the Mouthoumet Massif (Variscides, S-France): interference of orogenic accretion and crustal extension

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The Mouthoumet Massif represents a stepping stone between the Montagne Noire (at the southern margin of the French Massif Central) and the Pyrenees. The original tectonic pile of SE-facing folds and thrusts has been reduced, by subhorizontal extensional detachments, into seven tectonic units (in order from bottom to top and from W to E: Ia + b, IIa + b, III, IVa + b).

As already demonstrated by previous studies (1,2), facies and biostratigraphic ages of the Carboniferous beds (including the flysch) largely conform with that of the Montagne Noire. Refined mapping and conodont dating in unit Ib documents a deepening-upwards sequence of Devonian carbonate facies which closely resembles that of the Montagne Noire, but reveals a diachronous shift of lithological boundaries towards younger ages. This indicates that crustal extension occurred later than in the Montagne Noire.

The tectonic inventory of the individual units reveals early ductile top to the NNE movements (dextral transtension?) followed by SE-facing folds and thrusts, renewed extension (subhorizontal brittle detachments top NNE-WSW-SE) and open refolding.

A study of very-low grade metamorphism ("crystallinity" of clay minerals, KI) documents relatively high metamorphic temperatures at the top and especially at the base of the tectonic pile, with moderate temperatures in the middle. Unit I reveals a dramatic syn-tectonic geothermal gradient, with a change from epizonal to lower anchizonal conditions within less than 500 m. Rather uniform b0 indices around 9.01 are very similar to those observed in the metamorphic core complex of the M. Noire.

Ordovician sedimentary facies and K/Ar ages of 360 Ma indicate that the highest unit (IVb) was imported as a nappe from a more internal position in the Variscan orogen and emplaced over less metamorphosed rocks. In the underlying units, K/Ar ages attributable to Variscan crustal

stacking decrease down-section to c. 310 Ma in the deepest unit. Given a grossly southward transport of the original thrust nappes, this sequence documents southward propagation of the tectonic front.

In Units IIa and b, K/Ar dating and geological findings reveal that Variscan folding and thrusting occurred at c. 330 Ma, immediately after flysch sedimentation. This indicates deformation of crust heated already before the onset of stacking.

K/Ar dating also reveals thermal overprints around 275 Ma (Permian, lower part of Unit I), 300 Ma (Stefanian, lower part of Unit III), 310 Ma (Westfalian, upper part of Unit III) and 330 Ma (Namurian, western/lower part of Unit IVb). A post-tectonic microgranite body in the tectonic window of Treilles (E of the main Mouthoumet outcrop) yielded a Laser-ICP-MS age of 303 Ma, which probably represents the same thermal event as the c. 300 Ma K/Ar ages.

Taken altogether, the evidence presented suggests that the Mouthoumet Massif represents the southwestern termination of a hot metamorphic dome structure, which is probably continued in the Montagne Noire (3). Most of the metamorphic evolution is unrelated to Variscan crustal stacking, but relates to pulsed mantle activities, probably connected with incipient Tethys rifting (4).

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Extrusion tectonics from an intracontinental subduction zone: The late orogenic granites of the Saxo-Thuringian Zone

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The Allochthonous Domain of the Saxo-Thuringian Zone constitutes a Variscan nappe pile that was finally affected by the emplacement of various (ultra)-high pressure units at different middle to upper crustal levels. Their common feature, *i.e.* (U)HP metamorphism of continental crust at ca. 340 Ma, is indicative for an intracontinental subduction zone setting at the final collisional stage at the Bohemian Massif (Kroner and Romer, 2013). Coeval with and subsequent to the exhumation process, voluminous syn- and postkinematic granites evolved (ca. 338-318 Ma). Due to the spatio-temporal differences and distinct geochemical signatures, classically the granites of the different regions are considered as genetically autonomous. Here we introduce an evolutionary model for the generation of the postcollisional granites of the Saxo-Thuringian Zone explaining the variability of the granites with the interplay of advective heat transfer during the subduction-exhumation process and differences in the melt source.

The intrusion of the synkinematic granites (ca. 338-333 Ma) is spatially related to the initial extrusion of high-pressure/ultrahigh-temperature complexes. The K-rich Meissen Massif includes material from the continental lithospheric mantle and intruded along the late Variscan crustal scale strike-slip fault of the Elbe Zone. The coeval isothermal emplacement of the adjacent HP/UHT Saxon Granulite Massif is accompanied by synkinematic anatexis melts in the roof detachment. Granitic dykes and stocks cutting the core of the granulite massif constitute mainly molten felsic granulites indicating a fluid source beneath the massif. The release of these fluids is probably related to prograde LP/HT metamorphism beneath the hot granulites due to the thrusting onto low grade metasediments.

The voluminous postkinematic granites of the Erzgebirge-Fichtelgebirge Zone constitute different laccoliths intruding the nappe pile. The country rocks contain already exhumed (U)HP units. Because there is tectonic as well as geophysical evidence of the existence of voluminous UHT/HP units beneath the Erzgebirge-Fichtelgebirge Zone, we propose the former existence of a hot, E-W striking extrusion channel beneath the exposed part of the Allochthonous Domain (ca. 330-320 Ma). Advective heat transfer caused high temperature melting of tectonically accumulated lithologies and the subsequent emplacement in higher levels. The geochemically different granites display different sources. This can be exemplified by the formation of the Sn-W specialized granites of the W-Erzgebirge (Romer and Kroner, 2015). These highly specialized granites evolved exclusively in the region that is characterized by a vast antiformal stack of Sn-W enriched metasediments. The geochemical fingerprint of the Ordovician protolith is inherited by the granite.

Our model predicts that extrusion tectonics from the intracontinental subduction zone lasted over a time span of at least 20 Myr. Hence, the Saxo-Thuringian Zone contains continental crust highlighting the importance of mass and heat transfer from late orogenic subduction zones during the final thermal and gravitational equilibration of collisional orogens.

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Permian high-temperature metamorphism in continental units of the Western Alps (Italy)

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Following the Variscan orogeny the Adriatic margin underwent lithospheric thinning accompanied by asthenospheric upwelling, causing a high thermal regime within the continental crust. This produced high-temperature, medium-pressure (HTMP) metamorphism and partial melting in the lower crust as well as extensive magmatic activity affecting all crustal levels.

Evidence for an Upper Paleozoic regional metamorphic imprint is extensively recorded and well established in the Southern Alps and in Austroalpine units of the Eastern Alps. In the Western Alps, Permian metamorphism has been repeatedly inferred for Adria-derived units, but the age of this HTMP metamorphism has been only very locally constrained (Zucali *et al.*, 2011; Manzotti *et al.*, 2012). The present study aims to add reliable age data for this regional metamorphism. The main focus lies on the Valpelline Series and the IIDK (Sesia-Dent Blanche nappes), as they correspond to lower to middle continental crust, where the Permian metamorphic imprint was strongest and the Alpine imprint is rather weak. A limited number of samples from eclogitic micaschists of the Sesia Zone and the Emilius Klippe were also included in this study.

Here, an extensive dataset of U-Pb ages for metamorphic zircon is presented. To estimate *P-T* conditions of this metamorphism, the age data are complemented by Ti-in-Zrn-thermometry, Zr-in-Rt-thermometry and with *P-T*-information based on mineral assemblages. Clastic metasediments (mostly metapelites) were sampled to ensure sufficient amounts of zircon and to allow comparisons within the dataset.

The studied zircons show growth zones with textural features typical for metamorphic growth such as dark

CL-emission, indicating high Uranium content, and sector or fir-tree zoning. Some zircons also preserve detrital cores with a wide range of ages and textures. Growth zones related to the Permian metamorphism range in age between 310-260 Ma. However, individual samples often show zircon growth in two or three age generations within this time interval. Ages older than 300 Ma, reflecting an early/first phase of zircon growth, are sparse.

The main crystallisation phase of zircon, present in all samples, was between 290-270 Ma whereas younger ages (<270 Ma) are once more not found in all samples. Ti-in-Zrn-thermometry yields temperatures between 650-800 °C, whereas Zr-in-Rt temperatures are slightly higher, 650-850 °C. Taken together with preserved mineral assemblages (Grt + prismatic Sill + Bt + Pl + Qz + Kfs + Rt + Zrn + Fe-Ti oxides) these temperature estimates suggest upper amphibolite to granulite facies conditions for the Permian metamorphism.

Kyanite is absent in the mineral assemblages, and cordierite formed on retrogression; these observations indicate a pressure range between 5-11 kbar.

The data presented show that Permian HTMP metamorphism is abundant and widely distributed also in the Western Alps, in units derived from the Adriatic margin. The age and *P-T* estimates show many similarities with data reported for the Southern Alps, notably the Kinzigite Formation in the Ivrea Zone.

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Partial melting and continental subduction: coupling metamorphic reactions and collisional dynamics

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Partial melting is considered as a first order weakening mechanism for continental crust based on experimental evidences, and is actually the first metamorphic reaction that has been implemented in thermo-mechanical models of convergence zones. We performed two-dimensional numerical models of plate subduction and collision inspired by the Scandinavian Caledonian orogeny to investigate the possible impact of continental crust partial melting on the exhumation of Ultra-High Pressure metamorphic rocks. Three possible reactions were tested: low temperature solidus representing H₂O-fluid-saturated partial melting, and two end-member reaction curves for dehydration melting. Among the 3 tested reactions, only H₂O-fluid-

saturated partial melting drastically modifies the collision dynamics from the non-melting reference model holding all other parameters constant. Low temperature melting indeed induces the development of a low viscosity buoyant plume prior to slab detachment, where migmatites exhume from UHP conditions at rates and with pressure-temperature paths similar to the natural values acknowledged for the Norwegian Caledonides. Even if minor in terms of amount of magma produced, H₂O-fluid-saturated partial melting at UHP conditions could therefore have a dramatic rheological effect and actually limits continental rocks subduction and facilitates their exhumation.

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U-Pb dating of Variscan igneous rocks from the eastern French Massif Central: southward migration of coeval crust- and mantle-melting witnesses late-orogenic slab retreat

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The final stages of continental collision are key settings for continental crust formation and differentiation. This context is characterized by the emplacement of voluminous granitoid magmas, derived from both crustal and mantle sources and selectively preserved in the geological record. This situation is well-illustrated in the Variscan eastern French Massif Central (FMC), where abundant granitic bodies, including the >100 km-wide Velay complex, intruded coeval with mantle-derived “vaugnerites” during the Carboniferous, late-orogenic evolution immediately following the ~340 Ma collision. In order to better constrain the geodynamic evolution of this part of the Variscan belt, we studied the timing relationships between mantle and crust melting using new LA-ICP-MS U-Pb ages on zircon and monazite from igneous rocks of the eastern FMC.

We selected samples from four groups of plutonic rocks identified in the eastern FMC, namely: (1) peraluminous cordierite-granites (CPG; $n = 9$); (2) peraluminous muscovite-granites (MPG; $n = 3$); (3) per- to metaluminous biotite- and amphibole-granitoids (KCG; $n = 4$); (4) vaugnerites ($n = 15$). CPG and MPG represent the crustal end-member. Whole-rock compositions and age distribution of inherited zircons show that they derive from mixed lithologies of the local nappe pile, i.e. late Proterozoic to early Paleozoic ortho- and paragneisses of the Upper and Lower Gneiss Units. In contrast, KCG and vaugnerites are more mafic and devoid of any zircon xenocryst, suggesting that vaugnerites most likely represent enriched mantle-derived magmas, and KCG their differentiated products.

U-Pb dating (Fig. 1) does not reveal any correlation between ages and rock types. The range of intrusion ages are identical for granites (337 ± 2 Ma to 299 ± 2 Ma) and vaugnerites (336 ± 2 Ma to 299 ± 1 Ma), showing that coeval crust and mantle melting took place throughout the eastern FMC over nearly 40 Ma. There is, however, a clear southward migration of such magmatism during this period (Fig. 1), as indicated by ages of 336-334 Ma in the Lyonnais area, 337-326 Ma in the Forez and Livradois mountains, 322-308 Ma around the Velay dome, 313-309 Ma in the Margeride area and 306-299 Ma in the Cévennes, for both granites and vaugnerites. The Velay complex itself, and associated vaugnerites, yield ages of 303-299 Ma, thus marking the very end of this evolution.

This new dataset clearly shows that a thermal anomaly, affecting the whole lithosphere, migrated from the North to the South of the studied area throughout the Carboniferous. This conclusion is consistent with new models, based on field constraints and tectono-metamorphic data, suggesting that such anomaly may be related to the progressive retreat of a lithospheric mantle slab initiated in the late Devonian at the transition from continental subduction to collision (360 Ma exhumation of HP relics and granulites in the Lyonnais area) and propagating southwards until the late Carboniferous (Fig. 2). Lithospheric slab retreat resulted in an increase of the heat flux from the (asthenospheric) mantle, accounting for extensive 305-300 Ma lower crustal melting witnessed by the formation of the Velay complex (Fig. 2).

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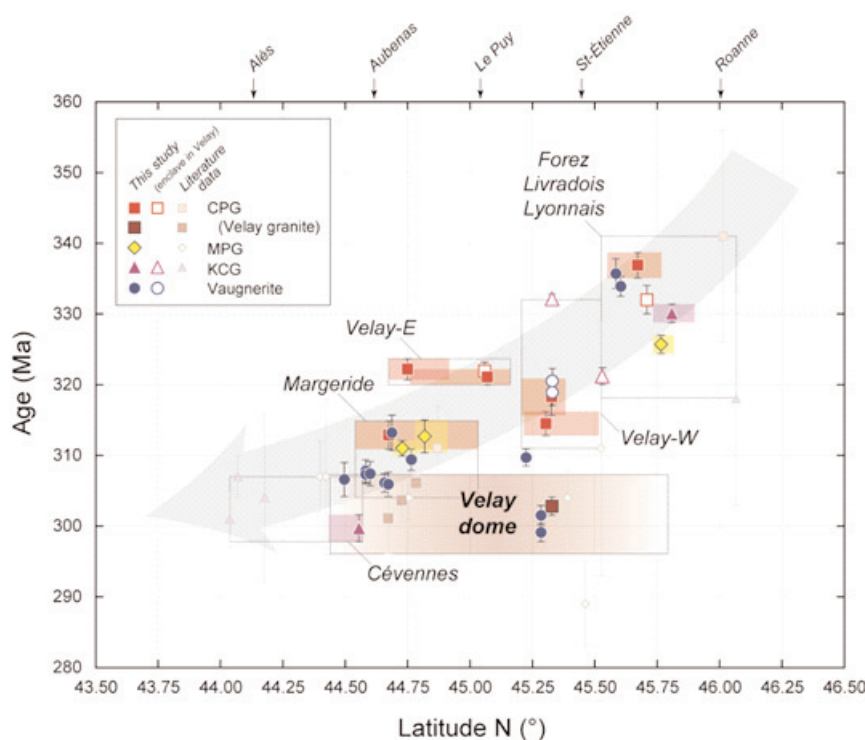


Fig. 1.- Plot of U-Pb intrusion age versus North latitude for samples of the eastern FMC. Shaded boxes represent the age and geographic extent of individually dated plutons or batholiths; dashed boxes schematically separate the different geographic domains.

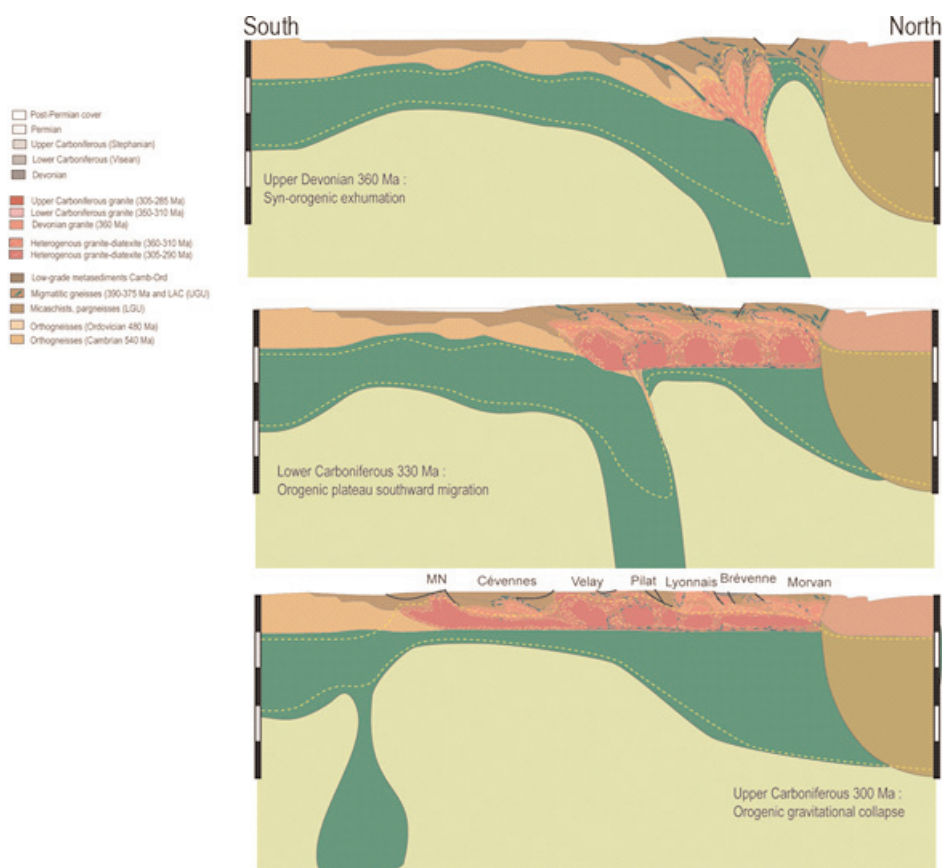


Fig 2.- Geodynamic model for the orogenic evolution of the eastern FMC between the late Devonian (upper panel) to the late Carboniferous (lower panel).

Signification of the late-Variscan high temperature event: a view from the Pyrenees

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After a classic succession of subduction and collision with formation of eclogites and high pressure granulites, the geological history of the variscan orogen is marked by a late high temperature - low pressure (HT-LP) event. In the pyrenean variscan segment, no subduction episode could be evidenced, and the collision stage is limited in intensity (no stacking of crustal nappes, no HP, moderate crustal thickening) and is short and rapidly followed by the late HT event. While the absence of HP stage will place the Pyrenees in an external zone of the variscan orogen, it remains that its singularity is the predominance of the HT event. The Pyrenees constitute therefore a key location for the study of the late variscan HT event. A review of the existing data shows that in the Pyrenees, the thermal peak is synchronous to slightly younger than the transition between syn- and post-orogenic sedimentations (Fig. 1). Consequently, an important part of the pyrenean variscan history can be described as 'post-orogenic' and takes place at the Carboniferous-Permian transition. This late HT event is expressed by a combination of HT-LP metamorphism, a main deformation phase, and the emplacement of magmas of various nature (basic, intermediate and acid) and of unknown origin. Various data indicate that the heat source which produced the thermal anomaly must be searched below the crust. The absence of significant thickening as well as the short timespan between the thickening and the temperature peak (Fig. 1) preclude a crustal origin by radiogenic heating. A potential heat source is the intrusive magmatism, which is mainly characterized

by large 'calcaline' granodioritic plutons emplaced at ca. 305 Ma (Denèle *et al.*, 2014). The chemical diversity of intrusive rocks suggests a mixed mantle-crustal origin of the magmas. However, despite the important volume of magmatic rocks, the cross-cutting relationship between contact and regional metamorphism isograds argues against a magma-induced HT-LP metamorphism. All these data imply a deep infracrustal origin of the thermal anomaly (crust-mantle boundary, lithospheric or asthenospheric mantle) which is probably linked to a specific geodynamic context at the scale of the south-european variscide (ST BLANQUAT *et al.*, 1990). The aim of our work is to quantify the development of the thermicity both in time and space at the scale of the variscan pyrenean crust, in order to constrain the geodynamic context that produced this thermal anomaly. We will present a synthesis of geochronological and geochemical published data obtained in the variscan pyrenees, and our first new results about the PTtd evolution of the north-pyrenean granulitic massifs (Saint Barthélémy, Bessède de Sault and Ursuya).

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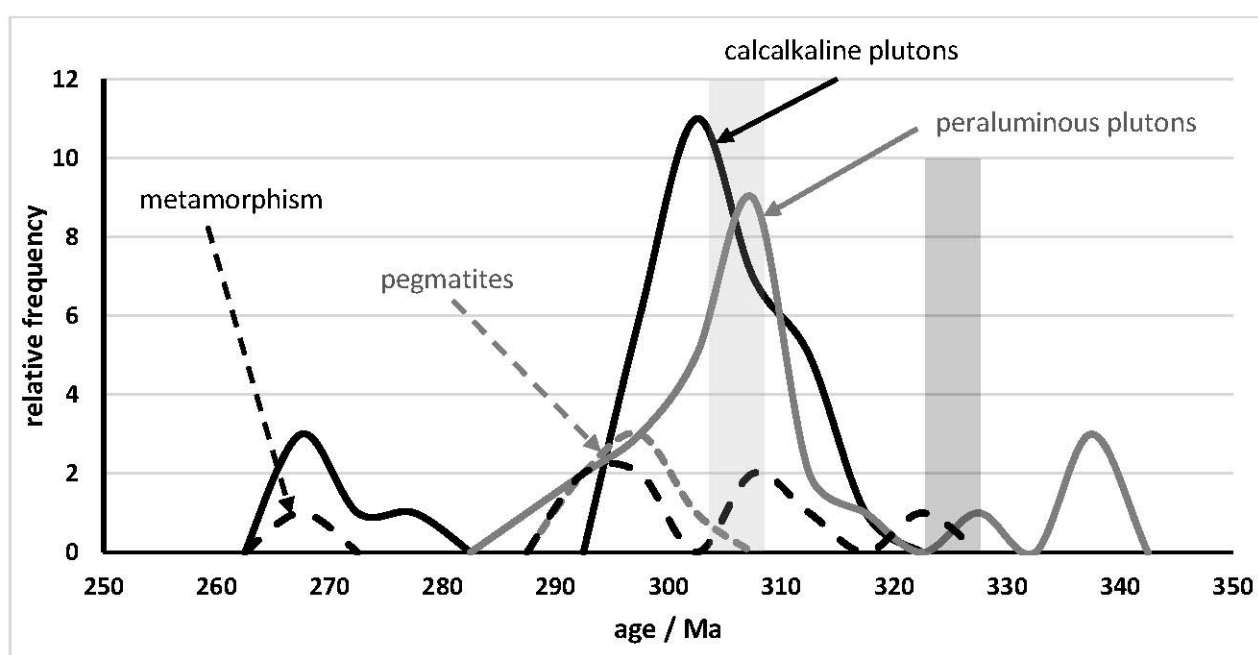


Fig. 1.- U-Pb age distributions in the Variscan Pyrenees.

Dark and light rectangles represent respectively the beginning of the syn-orogenic sedimentation and the limit between syn and post-orogenic sedimentations. Volcanic ages are not represented because they occur throughout Carboniferous and Permian

P-T evolution of Variscan high-pressure rocks from the Northern Malpica-Tuy shear zone in NW Spain

LI Botao

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The Malpica-Tuy zone (MTZ) in NW Iberia is a major shear zone containing abundant high-pressure (HP) metamorphic rocks such as eclogites and blueschists (Fig. 1). According to age dating results (Abati *et al.*, 2010, and references therein), these rocks were metamorphosed in Late Devonian times probably as the result of the collision of northern Gondwana with the Avalonian realm of Laurussia. A few rocks of the MTZ have been studied petrologically to obtain pressure(P)-temperature(T) data of their metamorphic evolution (e.g. López-Carmona, 2013). However, P-T paths, for instance, of eclogites are poorly known for the MTZ. For this reason, we want to add such paths for various kinds of HP rocks from the MTZ to better understand the Late Devonian collisional process. Here we present results for the MTZ related to an eclogite body and its surrounding gneiss some km southeast of Malpica (Fig. 1).

The eclogite contains the assemblage garnet, omphacite, barroisitic amphibole, rutile, ilmenite, epidote, quartz, and phengite, which grew after the garnet core. The composition of the inner portion of this core is $\text{Alm}_{59}\text{Prp}_{13}\text{Grs}_{24}\text{Sps}_4$; that of the outer core is $\text{Alm}_{57}\text{Prp}_{13}\text{Grs}_{27}\text{Sps}_3$. The garnet rim composition is $\text{Alm}_{57}\text{Prp}_{13}\text{Grs}_{30}\text{Sps}_1$. The gneiss is a former granodiorite now composed of quartz, plagioclase, K-feldspar, biotite, phengite, garnet, and epidote. Garnet is chemically zoned with $\text{Alm}_{26.3}\text{Prp}_{0.2}\text{Grs}_{70}\text{Sps}_{3.5}$, $\text{Alm}_{33.8}\text{Prp}_{0.7}\text{Grs}_{64}\text{Sps}_{1.5}$, and $\text{Alm}_{42.6}\text{Prp}_{1.4}\text{Grs}_{54}\text{Sps}_2$ as core, rim and outermost rim composition, respectively. P-T pseudosections were calculated with the computer program PERPLE_X for the bulk-rock compositions of the studied eclogite and gneiss.

The pseudosections were contoured by isopleths of various chemical and modal parameters. Based on the mineral assemblages of the rocks, the chemical compositions mainly of garnet and phengite, and the modal compositions, P-T paths were derived for the studied rocks. The eclogite record an early metamorphic stage at P-T conditions of 22-23 kbar and 520-560 °C and was then slightly heated during exhumation (Fig. 2). In contrast, the granodioritic gneiss experienced HP conditions of only 13-15 kbar at temperatures of 600-650 °C. These conditions are nearly identical to that of the final stage of the eclogite.

The obtained P-T data suggest that the studied eclogite underwent HP metamorphism in a subduction zone, but the crust, of which the metagranodioritic gneiss was part of, was only moderately subducted probably as the result of a slab break-off process. Following the geodynamic concept by Massonne (2012), the eclogite was exhumed in a subduction channel. When this rock reached the top of this channel, it was captured between the aforementioned colliding continental plates, inserted in the crust of the lower plate, and further exhumed with gneisses of this crust in an exhumation channel.

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The Cadomian orogen: constraints of timing, orogenic zoning, and crustal growth based on U-Pb and Hf isotopes of detrital and magmatic zircon

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The Cadomian Orogen in the NE Bohemian and the northern Armorican Massifs shows a distinct orogenic zoning from recent NW to SE consisting of (i) an outboard sitting continental crustal unit comprising Neoproterozoic rocks associated with c. 2.0 Ga old Icartian Basement, (ii) a magmatic arc and a back-arc basin, (iii) a foreland or retro-arc basin, respectively, and (iv) the passive margin of the Back-arc basin. New U-Pb zircon ages of detrital zircon of Neoproterozoic to Fortunian siliciclastics from the Schwarzburg Antiform in the Saxo-Thuringian Zone (NE Bohemian Massif) identify the West African Craton as the hinterland for the Cadomian Orogen. U-Pb ages and Hf isotope data constrain timing of orogenic events and episodes of crustal growth of both the Cadomian orogen and the cratonic hinterland (Fig. 1 A & B).

Zircons were analyzed for U, Th, and Pb isotopes by LA-SF ICP-MS techniques at the Museum für Mineralogie und Geologie (GeoPlasma Lab, Senckenberg Naturhistorische Sammlungen Dresden), using a Thermo-Scientific Element 2 XR sector field ICP-MS coupled to a New Wave UP-193 Excimer Laser System. Hafnium isotope measurements were performed with a Thermo-Finnigan NEPTUNE multi collector ICP-MS at Goethe Universität Frankfurt (GUF, Institut für Geowissenschaften, Mineralogie) coupled to RESOLUTION M50 193nm ArF Excimer (Resonetics) laser system.

New U-Pb zircon ages of detrital zircon of Neoproterozoic to Fortunian siliciclastics from the Schwarzburg Antiform in the Saxo-Thuringian Zone (NE Bohemian Massif) identify the West African Craton as the hinterland for the Cadomian Orogen demonstrated by zircon populations in the range of 1.8-2.2, 2.5-2.7, 3.0-3.1, and 3.4-3.5 Ga. Dominant zircon population (c. 50-70 % in each sample) is derived from Cadomian magmatic arc activity in a time slice of c. 570-750 Ma. The magmatic activity of the Cadomian arc

became extinct at c. 570 Ma. Closure of the back-arc basin by arc-continent collision occurred between c. 570 and 542 Ma under the formation of a foreland (retro-arc) basin. A short-living remnant basin existed between c. 542 and 540 Ma. Granitoid plutonism at 539 to 540 Ma document the final pulse of the Cadomian Orogeny. Hf isotopes, calculated ϵ_{Hf} values and TDM model ages from detrital and magmatic zircon show, that during the c. 180 Ma long Cadomian magmatic arc activity juvenile arc magmas became contaminated by the recycling of Eburnian and Archaean crust. Mixture with continental crust is always present. The required geotectonic setting is a continental magmatic arc during the Neoproterozoic developed on stretched Archaean and Palaeoproterozoic (Eburnian) crust. In the West African crustal evolution it can be demonstrated, that during Eburnian orogenic processes (c. 1.8-2.2 Ga) in most cases a 2.5 to 3.4 Ga old basement became recycled. Archaean 2.5-2.9 Ga old magmas recycled a 3.0 to 3.4 Ga old crust. Zircons with an age of 3.0-3.1 and 3.4 Ga are derived from juvenile magmas. Two zircons aged at 2779 ± 22 and 3542 ± 28 Ma imply a recycling of pre-existing Eo-Archaean to Hadean crust and show T_{DM} model ages of 3.98 and 4.29 Ga, respectively.

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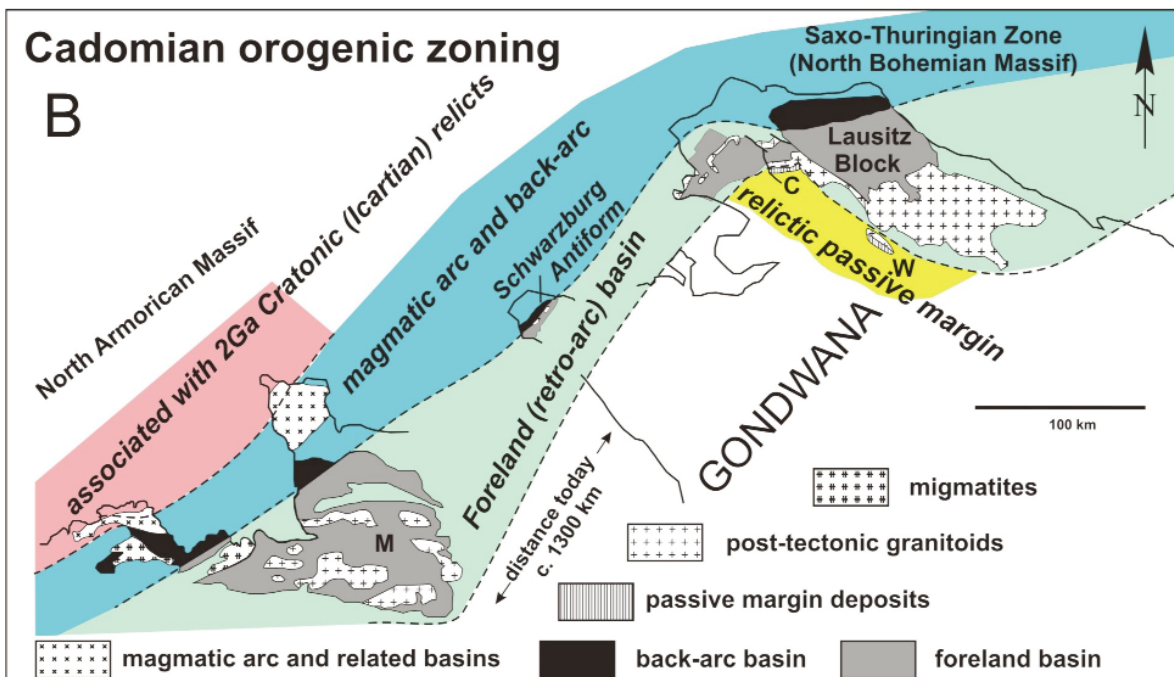
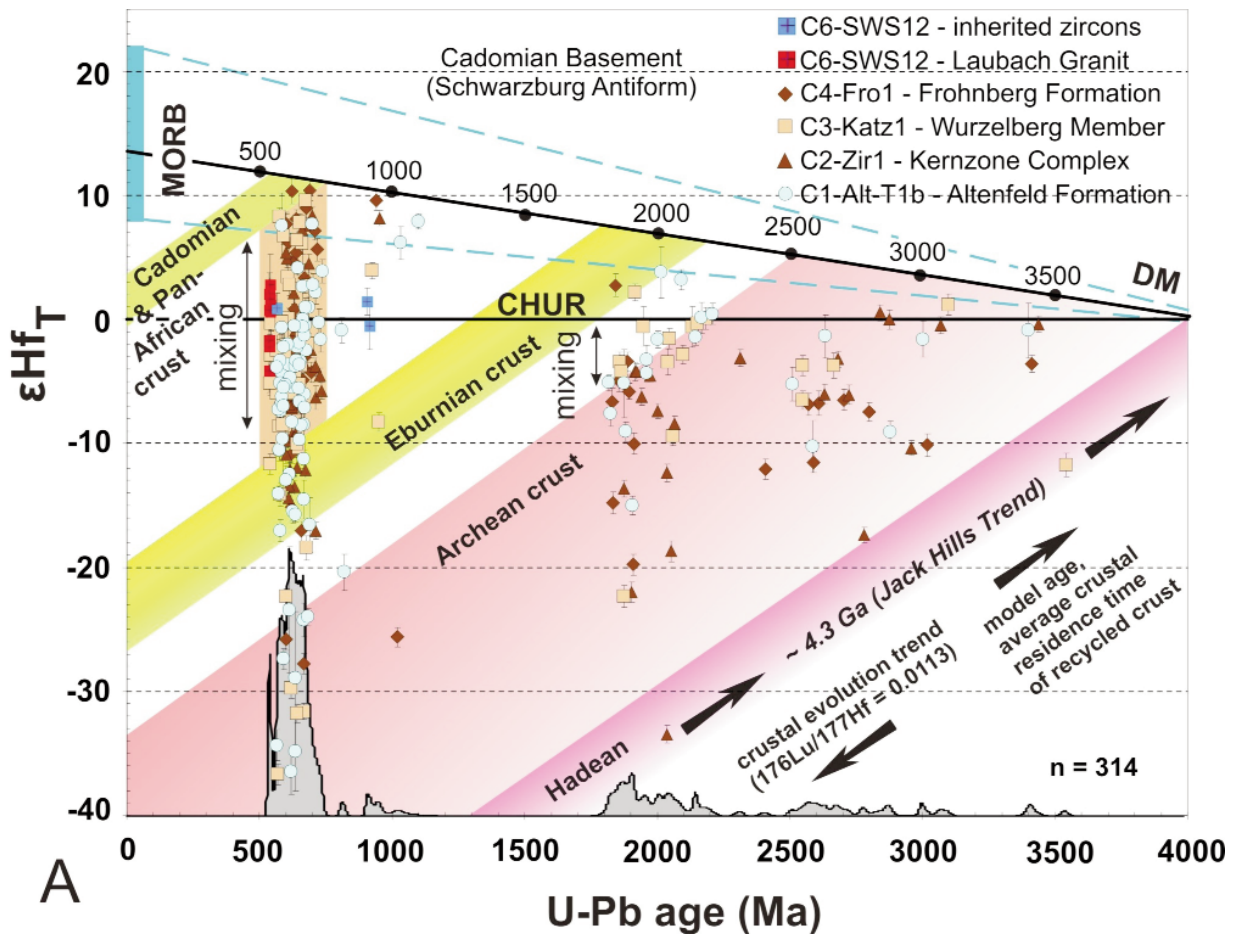


Fig. 1 A.- Hf isotope evolution diagram summarizing the data of zircon from all sedimentary rocks studied (from Linnemann et al., 2014). In addition, it also includes data from the Laubach Granite. The continental crust evolution trends of the main components of the West African Craton and the Cadomian orogen shown in different colors. The probability plot of the zircon age populations is represented in grey. For details and references of depleted mantle evolution see Gerdes and Zeh (2006).

Fig. 1 B.- Orogenic zoning of the Cadomian orogen in the northern parts of the Bohemian and Armorican Massifs (modified from Linnemann et al., 2008).

The eastern extent of the Hercynian orogenic belt: The history of the Istanbul Zone before and during the assembly of the Pangaea

LOM Nalan¹

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The Istanbul Zone, northwestern Turkey, consists of a Neoproterozoic (almost entirely Ediacaran) middle to high-grade crystalline basement with relicts of oceanic lithosphere, volcanic arc and continental crust of unknown affinity and it is overlain by a continuous, well-developed transgressive sedimentary sequence extending from the medial-late Ordovician to the early Carboniferous. The Paleozoic sequence commences with continental clastic sediments. The following thick arkoses are covered by U. Ordovician-L. Silurian feldspathic quartz arenite representing a low energy open shelf, probably tidal and beach environment. The basin became progressively deeper and more stable during the Silurian and Devonian. Lower-Middle Devonian nodular limestones show a transition from open shelf to a slope setting. Continuous deepening and deposition below the CCD conditions are marked by L. Carboniferous black lydites. The basin, which was tectonically stable from the Ordovician to the end of the Devonian, became a site of turbiditic flysch deposition and tectonically active during the Early Carboniferous. The Carboniferous flysch marks the progress of a collision. That collision created a dominantly (now) west vergent marginal fold and thrust belt on the eastern side of the Bosphorus and what now seems an east vergent (but with many inconsistencies) on the western side as a retrocharriage. The region of Istanbul shows essentially no metamorphism and only a weak cleavage development. The structural style of folds and faults requires a décollement underneath the whole city which thrusts the entire structure westward.

The Palaeozoic sequence is unconformably overlain by Permian and younger sedimentary strata. The Istanbul

Zone is separated from the Sakarya Zone by the Intra-Pontide suture and from the Strandja Massif by an inferred dextral strike-slip West Black Sea Fault. The Sakarya and Strandja fragments exhibit late Triassic and late Jurassic-early Cretaceous metamorphism and deformation.

The Palaeozoic sequences of Istanbul and Zonguldak have been compared and correlated with similar sequences in Europe, including the Moesian platform in Romania and Bulgaria, Moravo-Silesia (Brunovistulian) in the Czech Republic and the Rhenohercynian zone in Germany and Belgium, all deposited on the northern passive margin of the Rheic ocean. The Istanbul Zone is treated as a part of Avalonia. However, continuous transgressive sedimentation and absence of collision related magmatics or volcanoclastic sediments rule out this relationship. By contrast, the Istanbul sequence resembles the Pyrenees, the Carnic Alps, the Bohemian (Saxo-Thuringian) sequences and thus northern Gondwana-Land of the Palaeozoic times.

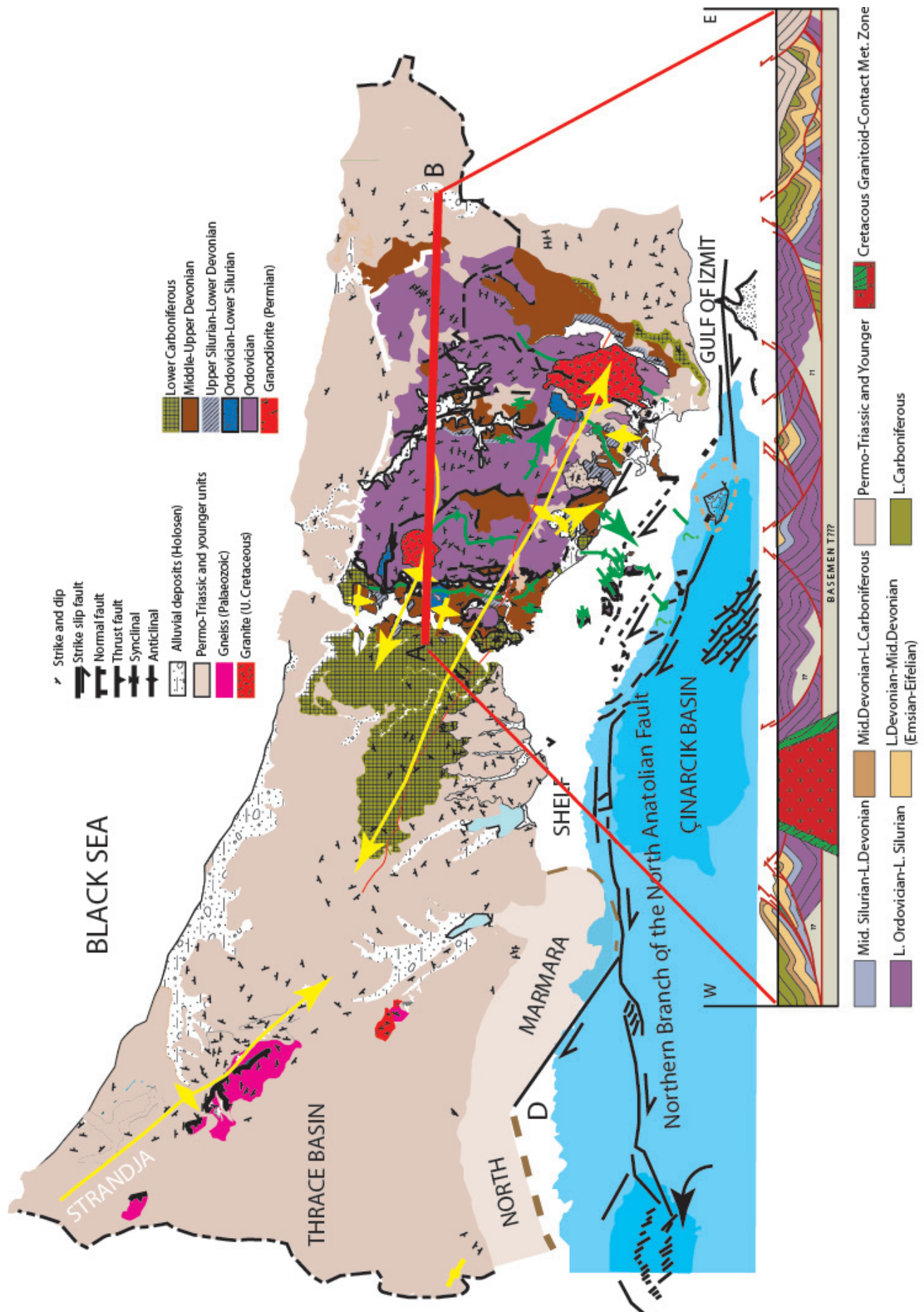
The zircon ages from its Neoproterozoic basement suggest that Istanbul Zone once was located at the northeastern margin of Gondwana-Land, recent paleontological studies place the Istanbul Zone to about 30-40°S for early Ordovician, however paleomagnetic studies indicate lower paleolatitudes, at about 16.4°S for the same time interval. Devonian fauna shows similarities with Thuringia, Rhenish Massif, Cantabrian Mts., Pyrenees, Holy Cross Mts. and North Africa. This ongoing debate requires a detailed structural analysis and more geological-geophysical sampling for the Istanbul Zone.

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High-pressure rocks in the Variscan belt of Western Europe: the Malpica-Tui Complex (NW Iberian Massif)

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Pods and relicts of high-pressure (HP) rocks are the best record of the subduction of the north Gondwana margin at the onset of the Variscan collision. Across Western Europe, blueschist-facies terranes are restricted to scarce and relatively small areas, whereas eclogite-facies terranes are more abundant.

The Malpica-Tui complex (MTC) is the westernmost exposure of HP rocks in the NW Iberian Massif, and in the Variscan belt of Western Europe. It comprises two tectonically juxtaposed units separated by an extensional detachment: (i) an upper unit consisting of rocks in the blueschist-facies, and (ii) a lower unit in the medium temperature eclogite-facies conditions. Assuming a northwest-directed component of subduction, in present day coordinates, the characteristics of each sequence suggest that the upper unit would occupy an oceanward position compared to the lower unit before the Variscan collision. Thus, the lower unit is interpreted as a slice of continental crust, whereas the upper unit may represent a transitional to oceanic crust of the same continental margin.

The MTC preserves evidence of late Devonian HP metamorphism varying from eclogite (P~26 kbar and T~650 °C) to blueschist-facies conditions (19-22 kbar and 460-560 °C). Petrological analysis involving P-T-X pseudosections in the (Mn)NCKFMASHTO chemical system on the HP rocks reveals a P-T evolution characterised by a subisothermal decompression to ~10 kbar, 480 °C in the blueschist-facies rocks and 650 °C in the eclogites, followed by cooling to ~5 kbar at 380 °C and 500 °C, respectively. New ⁴⁰Ar/³⁹Ar data indicate a minimum age of ~370 Ma for the subduction-related HP metamorphism. Subsequent decompression to pressures of about 10 kbar started at ~360 Ma and was contemporaneous with thrust-and-fold nappe tectonics and

intrusion of early Variscan granodiorites dated at ~350-340 Ma. Final, "post-nappe", exhumation is interpreted to have taken place from ~345-335 Ma to 320 ± 5 Ma, which is the age of the syntectonic igneous rocks emplaced in the autochthon of the MTC. These ages support the equivalence of the HP rocks from NW Iberia and their counterparts in the southern Armorican Massif.

From a methodological point of view, modelling calculations of H₂O and Fe₂O₃ on the metamorphic evolution of blueschist-facies rocks reveals trends that may have general applications in the investigation of rocks with similar composition: (i) subduction-zone metamorphism may occur in H₂O-undersaturated conditions induced by the crystallization of a significant modal amount of lawsonite, although the transition from lawsonite blueschist facies to amphibolite-greenschist facies may involve significant hydration, principally as a result of lawsonite breakdown. (ii) The analysed values of Fe₂O₃ may not reflect the oxidation state during the main metamorphic evolutionary stage and are probably easily modified by superficial alteration, even in apparently fresh samples.

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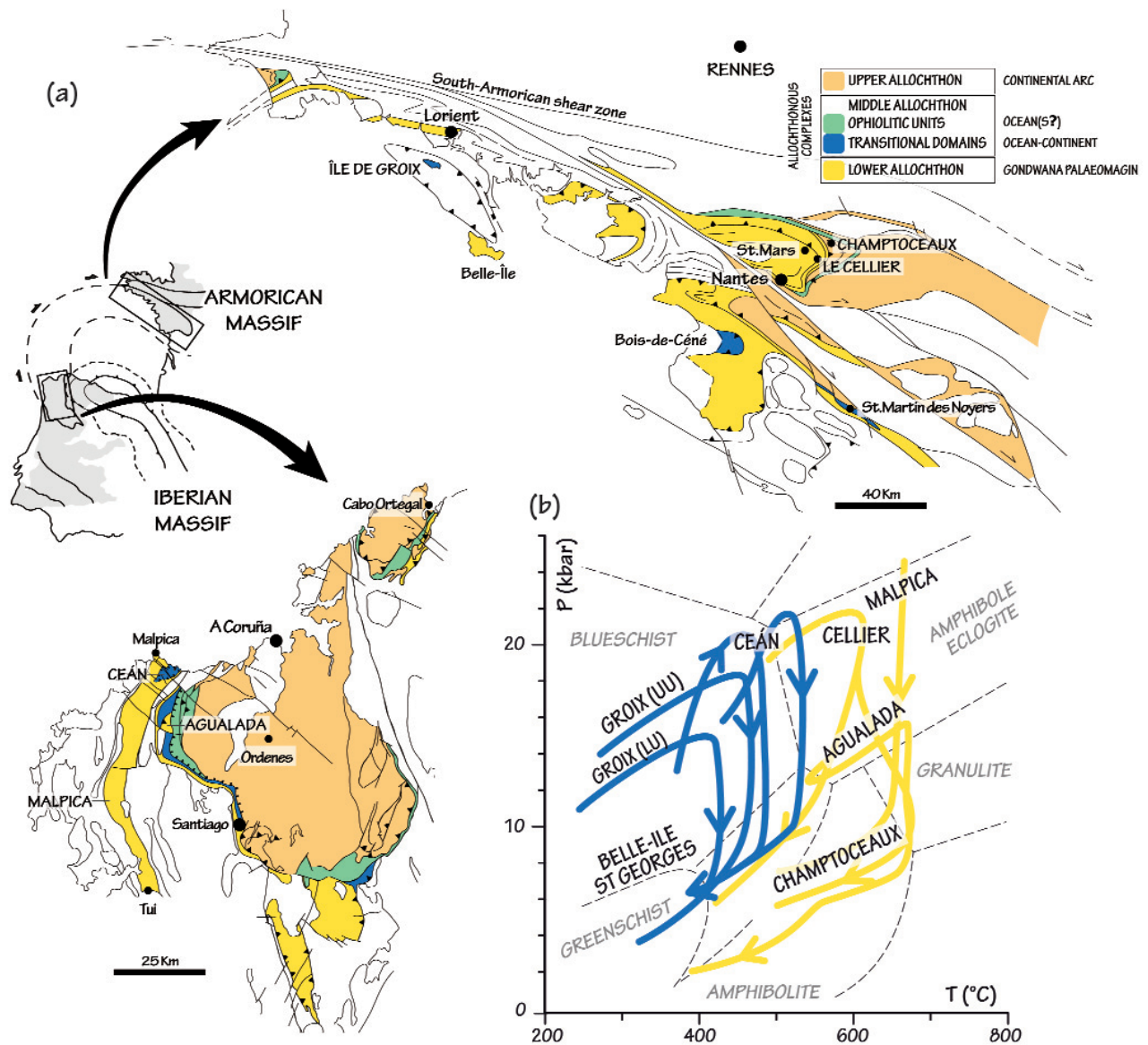


Fig. 1a.- Simplified geological maps of NW Iberia and the Southern Armorican Massif showing the distribution and correlation of the allochthonous domains. (b) Summary of the P-T paths from the blueschist- and eclogite-facies allochthonous units. Modified from Ballèvre et al. (2014) and López-Carmona et al. (2014).

P-T constraints in the internal domains of the Variscan Orogen through pseudosection modelling: the Barrovian section of Somosierra (Central Iberian Massif)

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The Somosierra region is located in the eastern Iberian Central System (ICS) and displays an almost complete section of upper and middle crustal rocks representing one of the most internal domains of the Variscan Orogen in the Iberian Massif. This region constitutes a landmark for the study of Barrovian metamorphism, and has been the subject of numerous studies over time (e.g. Macaya *et al.*, 1991; Escuder Viruete *et al.*, 1998; Rubio Pascual *et al.*, 2013).

Previous P-T-t paths determined in this region indicate a complex succession of processes during Variscan thickening and exhumation. Classical thermobarometric techniques applied to pelitic assemblages in the garnet, staurolite, sillimanite and sillimanite + Kfs zones show medium-pressure clockwise paths characteristic of mid-crustal levels in collisional orogens (Rubio Pascual *et al.*, 2013). Peak pressure conditions reached during D₁ (P~7 kbar; T~500 °C) are 4-5 kbar higher than those deduced from the thickness of the existent lithostratigraphic series (~6 km). Given that shortening produced by D₁ deformation does not exceed 50 %, the real thickening during metamorphism was 12-15 km larger than expected for this section. A recently published model explains the overburden by overthrusting of a large allochthonous sheet that might be subsequently thermally weakened and gravitationally extended, and thus was not preserved in the ICS (Rubio Pascual *et al.*, 2013). However, this allochthonous sheet would be preserved towards the NW Iberian Massif, in the so called Galicia-Trás-os-Montes Zone. This domain is formed by a succession of allochthonous units with Gondwanan affinity whose

thickness reaches 20 km and widely represented across the European Variscan belt (Martínez Catalán, 1990).

The thickness and the real existence of this inferred large allochthonous sheet above the ICS is highly sensitive to the accuracy of the thermobarometric constrains. Although conventional thermobarometry may provide reasonable results, likewise requires important simplifications and show several limitations. Thus, to try to further refine peak pressure constraints, a detailed study of the metamorphic evolution of representative samples of key mineral zones using pseudosection approach has been carried out. New data could help achieve a better understanding of the Variscan metamorphic evolution in the Somosierra region, as well as to progress in the optimization of the proposed geodynamic models.

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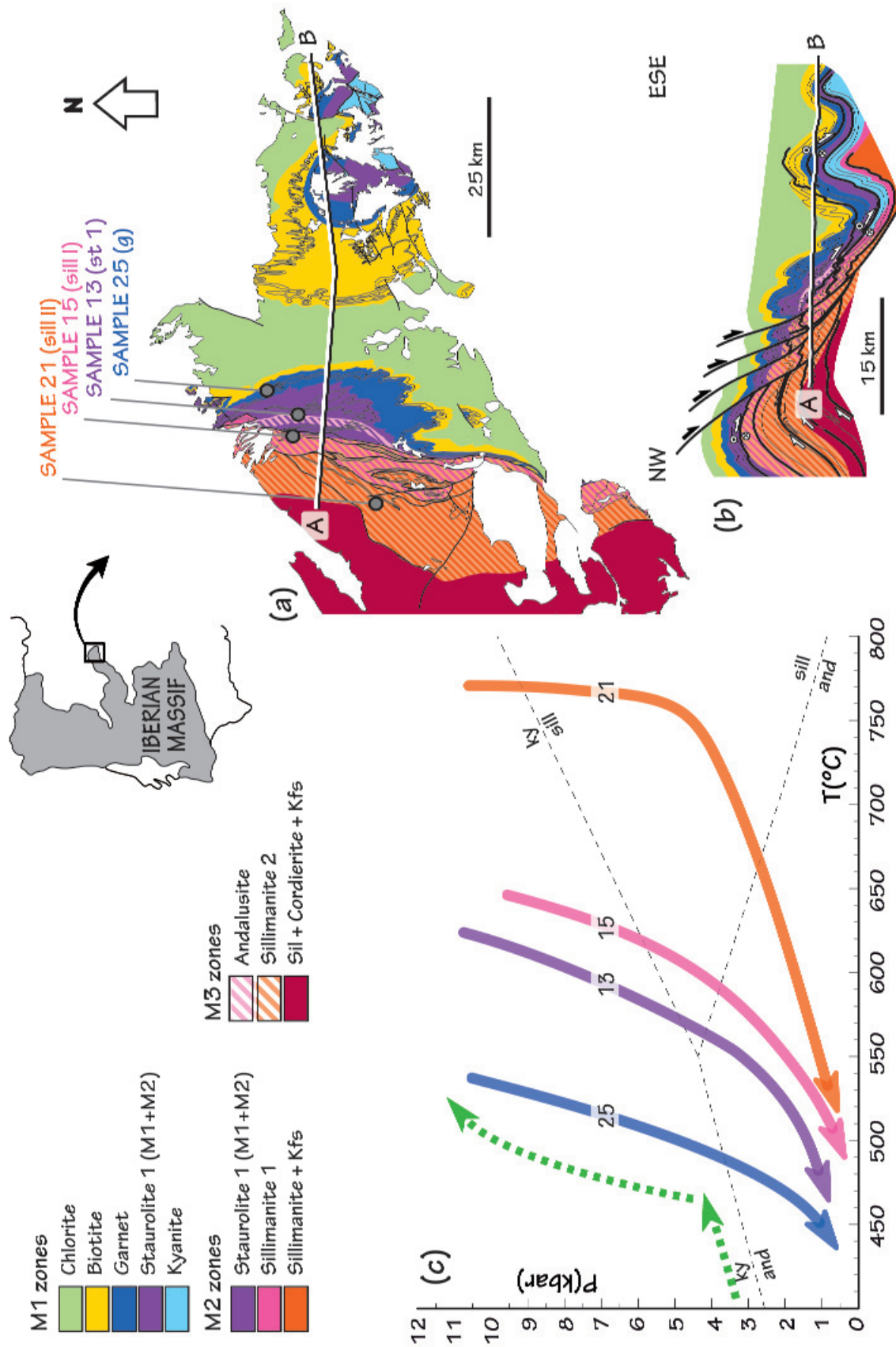


Fig. 1a.- Simplified metamorphic map and (b) cross section of the central part of the Iberian Central System. (c) Proposed P-T paths for the Somosierra region. Modified from Rubio Pascual et al. (2013).

Variscan subduction of an Ordovician granite : the Lévézou Massif, French Massif Central

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The Variscan Belt is usually interpreted as the result of an oceanic subduction followed by continental collision. The subducted ocean is represented by eclogitic lenses enclosed in amphibolite-facies rocks. This rock assemblage, called the Leptyno-Amphibolic Group (LAG), is considered as a suture unit that separates two different continental fragments (Upper Gneiss Unit, UGU and Lower Gneiss Unit, LGU). During the collisional stage, crustal thickening would have led to the emplacement of several synkinematic granites (e.g. Matte, 1986).

Such an interpretation has been proposed for the Lévézou area (southern French Massif Central, Fig. a) (Nicollet, 1978). The Pinet orthogneiss, initially dated at 360 Ma by lower intercept on zircon fraction (U/Pb, Pin, 1981), is intrusive in both the UGU and the LGU and was considered as a syn-kinematic granite contemporaneous with the Carboniferous thrusting (Pin, 1981; Burg *et al.*, 1984, Burg & Teyssier 1983).

Our recent observations show that the deformation pattern of this orthogneiss results from two superimposed deformations (see also Duguet and Faure, 2004) and do not correspond to C-S structures, symptomatic of synkinematic intrusions, as inferred previously (Burg & Teyssier, 1983). Its porphyric character confirms that the Pinet orthogneiss is not a synkinematic intrusion. Geochemical and geochronological analyses of the orthogneisses in both the UGU and the LGU show that they result from the melting of a common source and that they emplaced ca. 470 Ma ago (U/Pb dating on zircon external rims), during the early Ordovician. The geochemical signature of the orthogneisses and the mafic rocks of the LAG show affinities with a magmatic arc and its back arc basin, respectively.

In the least deformed orthogneisses, rectangular clusters

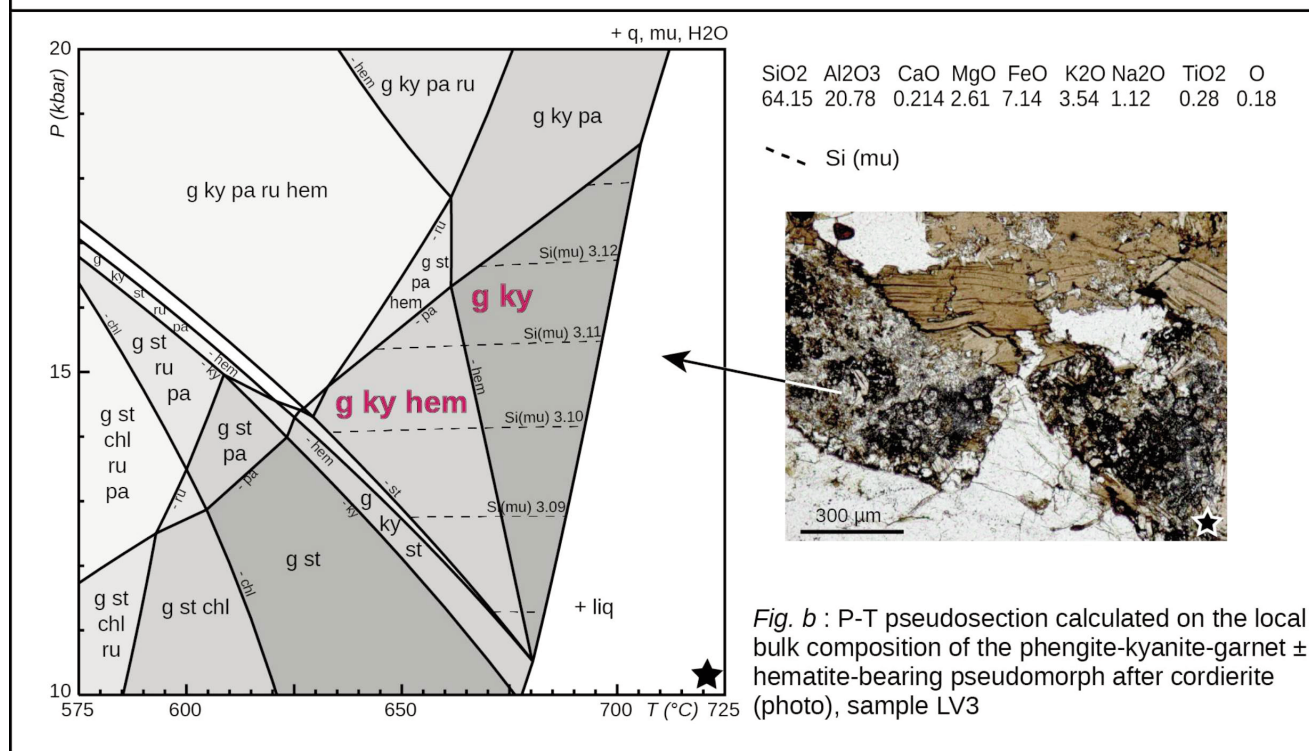
dominated by phengite, kyanite and garnet suggest a pseudomorphism of former crystals of magmatic cordierite (Fig. b). Phase diagrams calculated with THERMOCALC suggest that the pseudomorphs developed in eclogite-facies conditions (ca. 14-17 kbar, 650 °C, Fig. b). These conditions are similar to those obtained from the eclogite lenses of the neighbouring LAG. Both the orthogneisses and the LAG experienced the same high-pressure event. Preliminary Ar-Ar dating on muscovite grains from both orthogneisses show that the exhumation and deformation took place ca 340 Ma ago.

This suggests that Variscan tectonics in the Lévézou area corresponds to the subduction and accretion of a magmatic arc and associated narrow basins rather than a true continental collision.

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Linking PT evolutions of Bohemian Massif and Tibetan granulites through numerical modelling: insight to geodynamics of internal orogens

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Variscan orogeny is traditionally compared to Himalayan-Tibetan orogeny thanks to two main reasons: 1) Variscan orogen originated through progressive amalgamation of Gondwana derived blocks which formed belt that was subsequently squeezed between two continental plates - Laurussia and Gondwana. Similar sequence of events is characteristic for Tibetan-Himalayan orogeny as well, where previously Gondwana accreted blocks were squeezed between Asian continent and India. Therefore, both orogens result from similar reorganization of plates in Paleozoic and Mesozoic-Cenozoic times, which initiated rapid northward drift of Gondwana derived blocks and their final collision with northern continental masses. 2). This process resulted in both cases in formation orogenic root of double-crust thickness characterized by long lasting (HP) granulite facies metamorphism in lower crust followed by isothermal decompression still at granulite facies conditions. In addition, the granulites in central Tibet were transported by high potassium lavas, with geochemical and isotopic signature corresponding to Mg-K granitoids typically associated to HP granulites in the eastern part of the Variscan belt (the Bohemian Massif in particular). In both cases, the origin of granulitic lower crust is attributed to relamination and thermal maturation of lower crustal allochthon underthrust below upper plate crust during collision.

Based on above similarities we argue that the Devonian - Carboniferous evolution of the Bohemian Massif may be a

proxy of Eocene to recent crustal dynamics of the Tibetan system. To better quantify similarities between both orogens, we present a set of numerical models which reproduce the tectonic multistage scenario proposed for the Variscan tectonics of Bohemian Massif. These models are subsequently compared with *P-T* data acquired from the Himalaya and southern Tibetan granulites and xenoliths from central Tibet. The salient feature of the model is the vertical exchange of relaminated felsic lower crust with overlying material. The dynamics of vertical material and heat transfers is tested for variable density, heat production and viscosity of both relaminated and overlying crustal layers. The exhumation event is followed by development of a major zone of decoupling separating the orogenic superstructure from the deep orogenic infrastructure. This decoupling zone, called here the infrastructure-superstructure transition zone, is responsible for material and heat transfers resulting in development of sub-surface channel flow. Thermal structure of this zone suggests partial melting of mid-crustal rocks and formation of a thick migmatized layer which may correspond to partially molten middle crust that is supposed to exist beneath Tibetan plateau as indicated by some geophysical observations. Finally, we propose that numerical modelling constrained by direct geological observations of ancient orogens is a valuable tool for deciphering the internal dynamics of modern orogens where direct observations are lacking.

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Detrital zircon geochronology in blueschist facies meta-conglomerates from the Western Alps: implications for the late Carboniferous to early Permian palaeotopography

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In the Western Alps, the Money Complex of the Gran Paradiso Massif, metamorphosed under blueschist facies during the Alpine cycle, is considered to be Permo-Carboniferous in age, but no palaeontological or radiometric data constrain this interpretation.

A revision of the lithostratigraphy of the Money Unit allows recognizing a polygenic (graphite-rich) and a monogenic (graphite-poor) meta-sedimentary formation. Detrital zircon U-Pb geochronology in both meta-sedimentary formations shows that (i) the main population is Cambrian and Ordovician in age, (ii) the youngest grains are Silurian and Early Devonian and (iii) Carboniferous zircon grains are lacking.

A careful study of the age distributions in the Alps suggests that potential source for the detrital material in the Money

Complex is the Briançonnais basement. Late Carboniferous magmatism is widespread in the Helvetic Zone of the Alps. Permian magmatism is dominant in the Briançonnais, the Austroalpine and the Southalpine unit. The lack of Carboniferous zircons in the Money Complex suggests that the detritus was not shed from the Helvetic zone, which was separated from the Money basin by the Zone Houillère basin, where the main drainage pattern was developed from south to north and where the depocenters migrated northwards from the Namurian to the Stephanian.

We suggest that the Money Complex may have been located to the east of the main river drainage inside the Zone Houillère basin or alternatively may represent a small basin, located on the east of the Zone Houillère.

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Detrital zircon U-Pb ages in Variscan syn-orogenic deposits of NW Iberia: Relationships between sedimentation and emplacement of the Allochthon

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Flysch-type, Carboniferous syn-orogenic deposits were laid down in relation to the emplacement of a large allochthonous nappe stack in the Variscan belt of NW Iberia. New LA-ICP-MS U-Pb age populations of detrital zircons are considered together with previously dated samples (Martínez Catalán *et al.*, 2004, 2008) to establish the relationships between thrusting and sedimentation. The age populations of four syn-orogenic formations (Gimonde, San Vitero, Almendra and San Clodio), are compared with those of the pre-orogenic sequence in the Autochthon and Parautochthon, representing the Gondwana passive margin, and in the Allochthon, formed by peri-Gondwanan and oceanic terranes.

Furthermore, a new structural study has been carried out to understand the relationships between the syn-orogenic deposits and the development of Variscan structures. The aims are to identify the sources of sediments and to establish the relationship between Variscan structural evolution and syn-orogenic sedimentation.

The zircon age populations point to the Allochthon as the main source of detritus for the syn-orogenic basins, as shown by the scarcity of Mesoproterozoic zircons, the relative abundance of Paleozoic, pre-Variscan zircons, and the presence of early-Variscan and Variscan zircons in the syn-orogenic sediments. A limited participation of the Parautochthon and Autochthon in the younger formations is possible, as indicated by relatively young Variscan zircons.

The more internal syn-orogenic formations underlie the Allochthon and are pervasively imbricated in thrust sheets with the pre-orogenic Parautochthon. However, the more external of the studied formations, San Clodio, lies unconformably upon from the reverse limb of a previously developed recumbent fold, and is weakly affected by thrusting. This indicates erosion pre-dating syn-orogenic sedimentation at the front of the nappe stack, which can be explained by the development of a forebulge outwards from the allochthonous front, and of depocenters that hosted the syn-orogenic sedimentation.

Together with the trend shown by the more recent zircons in each formation, that are younger towards the external zones, the data suggest that sedimentation occurred in progressively migrating depocenters formed in front of the allochthonous wedge during its emplacement.

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Timing of rare-elements (Li-Be-Ta-Sn-Nb) magmatism in the European Variscan belt

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High-phosphorus peraluminous rare-elements granites and rare-elements LCT (Lithium, Caesium, Tantalum) pegmatites are the most important sources of raw materials for some critical metals like tantalum (1,2) represent important economic storehouses for industrial minerals like feldspar, quartz, mica or kaolin. They principally emplace in orogenic settings (3). A fast overview of three main European Variscan districts, i.e. the Moldanubian domain of the Bohemian massif, the French Massif Central (FMC) and the NW Iberia provides a basis for questioning the origin of rare-elements magmatism and the actual classification of rare-elements pegmatites, in particular the LCT pegmatites.

Granitic pegmatites are widespread in most of the Bohemian Massif but LCT pegmatites are most common in the Moldanubian domain. In this area, their emplacements seem mainly controlled by migmatitic domes and shear zones and correspond to two events (4). The older at 333 ± 3 Ma just follow HT-MP event of the end of the Moravo-Moldanubian phase and the younger at 325 ± 4 Ma is contemporaneous with beginning of the Bavarian phase (U-Pb ages on columbite and tantalite).

In the FMC, most of the actually known rare-elements magmatic bodies form a province in the North Limousin area, which represents the northwestern part of the FMC. U-Pb dating of columbite-group minerals from Beauvoir, Montebrias and Chèdeville rare-elements magmatic bodies leads to emplacement ages at 317 ± 6 Ma, 314 ± 4 Ma and 309 ± 5 Ma respectively. The contemporaneous Marche fault system (5), which crosscuts in a general E-W trend all the northern part of the Limousin, seems to be a key-structure for the rare-elements magmatism of the area.

Although rare-elements pegmatites are known in the different Variscan massifs of Iberia, the northwest part of the Iberian Variscan belt contains numerous fields that represent the first economic targets in Europe, particularly in the Central Iberian Zone (CIZ) and in Galicia-Trás-os-Montes Zone (GTOMZ). Three events of rare-elements magmatism have been recognized in Northwest Iberia (U-Pb on columbite and tantalite; 6): (i) emplacement of the Argemela rare-element granite, in the CIZ, with an age of 326 ± 3 Ma; (ii) intrusion of rare-element pegmatites from the GTOMZ at an average age of 310 ± 5 Ma; (iii) emplacements of rare-element pegmatites in the CIZ and in the southern GTOMZ at about 301 ± 3 Ma. Moreover, the observed southward propagation of ages of emplacement matches the propagation of deformation, metamorphism and magmatism in the two different geotectonic zones.

The spatial and temporal distributions of rare-element pegmatites in the Variscan belt suggest that rare-elements magmatism could be related to local specific conditions like particular sources, tectonic and thermal regimes.

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The Neoproterozoic-Cambrian transition in Abrantes Region (Central Portugal); Lithostratigraphic correlation with the Cambrian Series of Ossa-Morena Zone

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Abrantes region (Fig. 1A) presents a lithostratigraphic succession with clear similarities with typical sequences of Neoproterozoic-Cambrian transition in Ossa-Morena Zone (OMZ). Classical works have attributed Abrantes entire sequence to Neoproterozoic (e.g. Gonçalves *et al.*, 1979). Detailed characterization, based on fieldwork, of the stratigraphic succession allows to discriminate the presence of lithostratigraphic units, attributed to lower Cambrian by correlation with other localities of the OMZ (Fig. 1B); these units overly Neoproterozoic series.

The Cambrian sequence (Abrantes Group; Fig. 1C) begins with a volcano-sedimentary unit composed by detrital rocks, which includes meta-arkoses, meta-pelites and meta-psamites; some rocks show immature content. The volcanic component is mostly composed by abundant felsic rocks, generally with rhyodacitic composition (Abrantes Felsic Unit). The previous characteristics are common in OMZ, where a clastic unit (often missing), sometimes with felsic volcanics and conglomerates, overlies the Serie Negra succession, previously deformed during the Cadomian orogeny at Neoproterozoic times (e.g. Oliveira *et al.*, 1991; Nance *et al.*, 2012).

Abrantes felsic unit gradually change to a carbonate unit (S. Miguel do Rio Torto Carbonates), with calcitic and dolomitic marbles and interbedded mafic volcanics. This unit can be correlated with a range of carbonated units present in all OMZ (Fig. 1C). These units represent a carbonate platform during lower Cambrian showing the beginning of an oceanization process that culminates with the opening of Rheic in lower Ordovician times (Pedro *et al.*, 2010). The

lower Cambrian succession culminates with another volcano-sedimentary complex, poorly outcropping; the clastic succession of this complex is dominated by pelitic rocks, interbedded with bimodal volcanics. The transition between the carbonated sedimentation and the overlying volcano-sedimentary one is gradual. All the previous units have not fossiliferous content, mainly due to the action of metamorphic process, which reaches the amphibolitic facies.

With the aim of characterizing and correlating the lower Cambrian carbonate event in the OMZ, it is ongoing ⁸⁷Sr/⁸⁶Sr, ¹³C and ¹⁸O isotopic analysis (Isotope Geology Laboratory of Aveiro University and in the Stable Isotopes Laboratory of Lisbon University).

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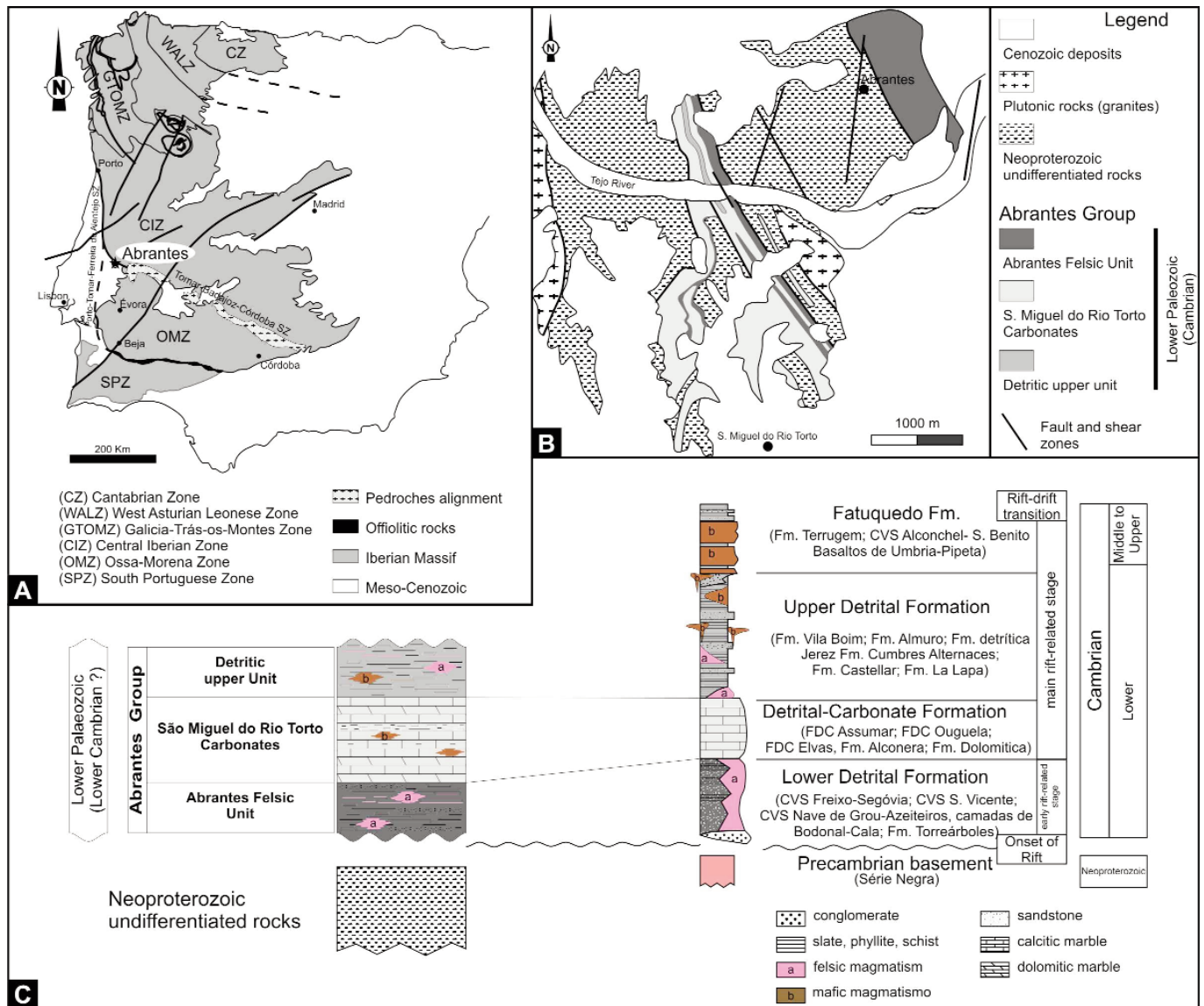


Fig. 1A.- Main divisions of Iberian Massif, signaling the geographic localization of study area; (B) Simplified geological map of Abrantes region; (C) Lithostratigraphic succession of Abrantes Group, attributed to lower Palaeozoic, and its comparison with generalized stratigraphic column of the OMZ (adapted from Nance et al., 2012).

Rifting the Gondwana: record of a thinned continental margin in the French Massif Central

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The French Massif Central is a nappe stack made of units chiefly derived from breakup of the Northern Gondwana. At the base of the Upper Gneiss Unit, the “Leptyno-Amphibolitic Complex” (LAC) is an Ordovician bimodal unit that was subducted, dismantled and submitted to Silurian HP-BT metamorphism. The underlying Lower Gneiss Unit comprises metasediments and Cadomian orthogneisses. Para-autochthonous units in e.g. the Cévennes are made of schists, with intervening units of meta lavas.

U-Pb ages from the LAC in the Eastern Massif Central (Tournon area, see Chelle-Michou *et al.*, this meeting) as well as in the Alps cluster around 475-480 Ma. Rhyolites layers in the para-autochthonous units (Faure *et al.*, 2009), as well as meta-rhyolites of the Lower Gneiss Unit (Melleton *et al.*, 2010) display the same age. This age is close, but not similar to the age of the Chamrousse ophiolite (ca. 495 Ma) in the External Crystalline Massif of the Alps (Guillot and Ménot, 2009).

Hf isotopes in zircons from the LAC reveal a bimodal origin, with an old crustal component as well as a juvenile component at ca. 480 Ma. A compilation of composition of mafic rocks of the LAC in the Massif Central reveals the presence of several components, including (1) a deep mantle source (garnet-facies); (2) a shallow mantle source (MORB-like); (3) a “crustal” component. The felsic components from the LAC are mildly peraluminous rhyolites originated from the Gondwana crust. Similar patterns of polybaric melting and bimodal magmatism are observed in modern passive margins such as the Vøring margin (of Norway) (Meyer *et al.*, 2009). The crustal input

may correspond either to interactions with existing continental crust during emplacement, or to a back-arc component.

Ordovician magmatism of the lower units is dominated by rhyolites, pointing to the major role of crustal melting. Subordinate mafic lavas in the lower units do not show any crustal contamination, and mostly evidence a deep mantle source, consistent with melting under the edge of a rifted continental crust.

Collectively, these evidence point to the UGU being an ultra-thinned continental crust, or crust on the ocean/continent transition. The LGU and para-autochthonous units in contrast would correspond to a more proximal section of the margin, a thinned continental crust overlaid by thick clastic sequences.

The age as well as composition of the LAC “ophiolites” are similar to mafic remnants along strike, in Brittany or external Alps. They are, on the other hand, distinct from e.g. the Chamrousse ophiolite, consistent with the presence of several small oceanic basins in the Southern Variscan suture, rather than one unique large ocean.

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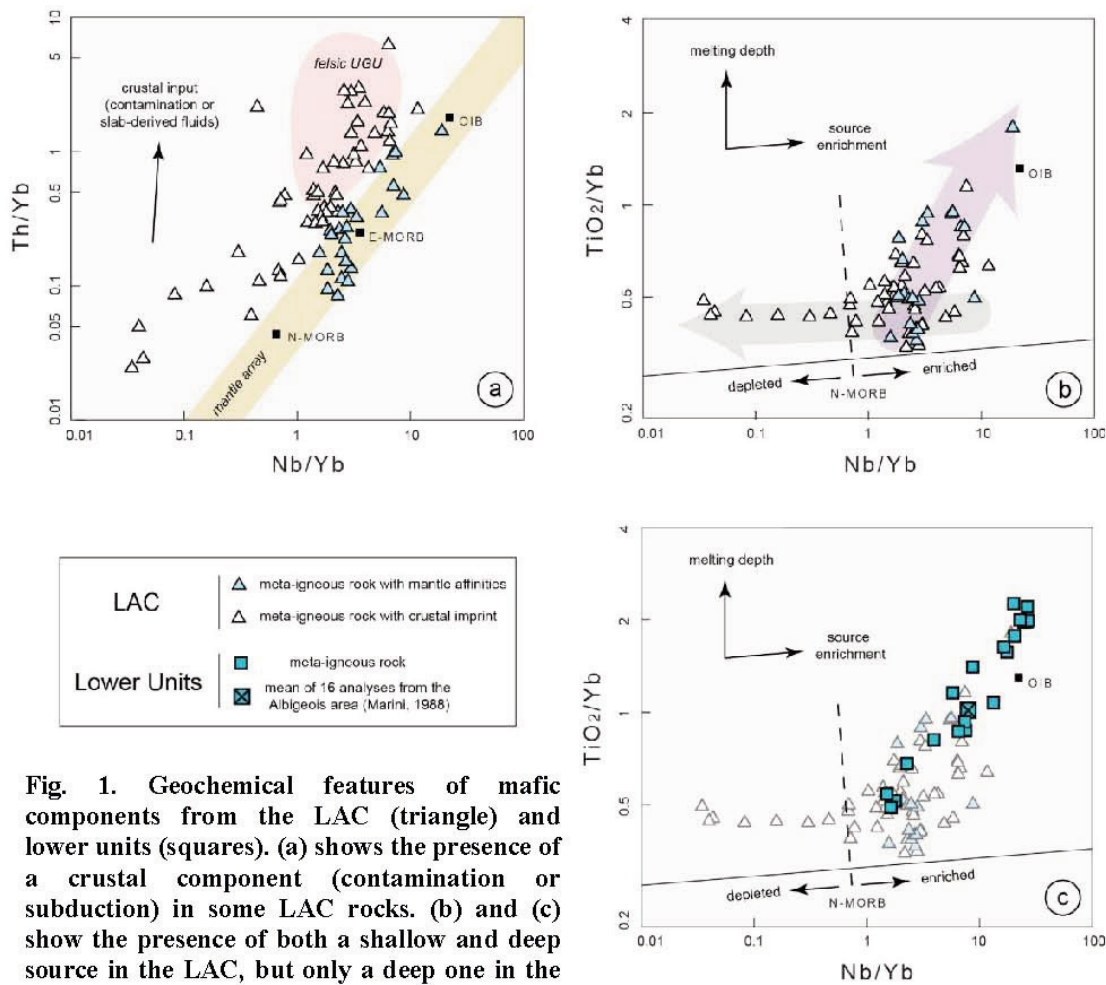
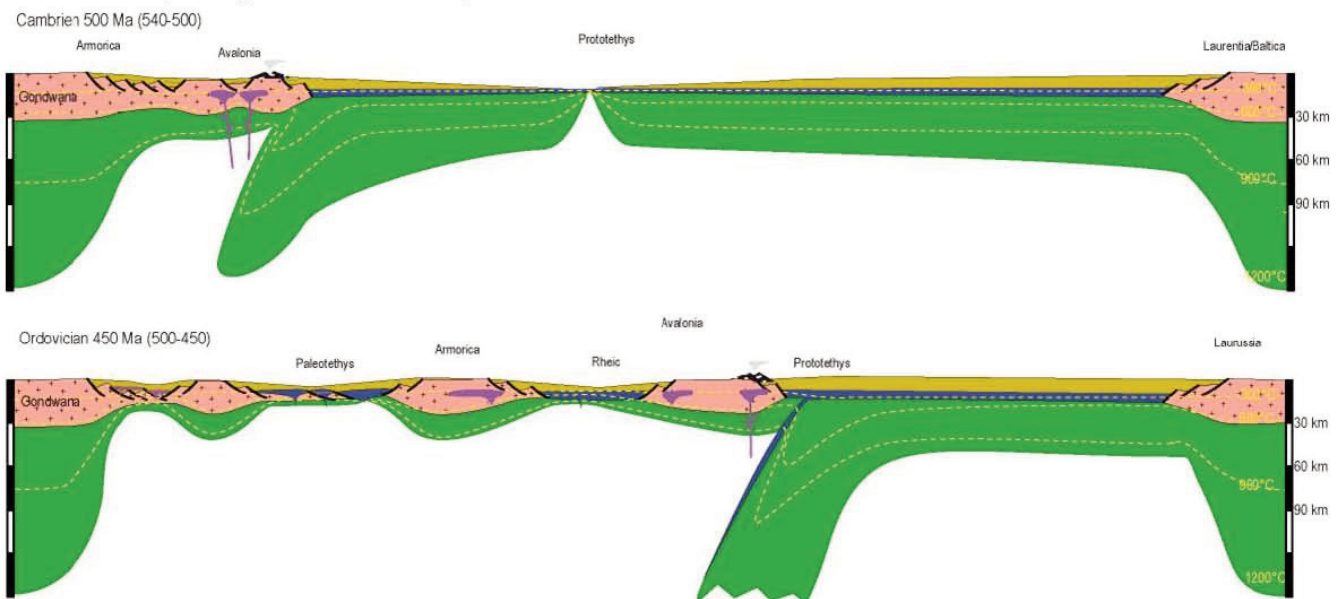


Fig. 1. Geochemical features of mafic components from the LAC (triangle) and lower units (squares). (a) shows the presence of a crustal component (contamination or subduction) in some LAC rocks. (b) and (c) show the presence of both a shallow and deep source in the LAC, but only a deep one in the lower units.

Fig. 2. Geodynamic sketch showing the thinned Gondwana margin during the Ordovician (and a possible subduction).



Ordovician reorganization of the European Gondwana: Towards an integrated magmatic – sedimentary – structural scheme across the Variscan domain

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Fragmentation of northwestern Gondwana took place in a context of massive and widespread magmatism during the Ordovician. With the improvement of U-Pb dating techniques, Ordovician plutonic and volcanic rocks have been increasingly documented throughout the Variscan orogen of Europe. The origin of this magmatism is largely debated or even mostly conjectural. It implies a lithospheric and most probably asthenospheric reorganization of the future Variscan domain that will impact the way in which convergence and collision will be recorded. The Ordovician sedimentary record, and particularly that of the “Sardic” unconformity also poses the issue of the potential links between external and internal geodynamics via lithospheric deformation during the Ordovician magmatic event.

The Ordovician is richly documented throughout the Variscan belt, but on numerous localities and mostly from a monodisciplinary perspective, notwithstanding the fact that the structural environment of Ordovician sediments,

plutons and volcanics has rarely been investigated. Our project (ORDISCO) aims at evaluating the coupling between internal geodynamics, crustal deformation and the sedimentary record during dynamic reorganization of the northwestern Gondwana margin later involved in the Variscan collision. It will include the implementation of a harmonized geodatabase gathering the magmatic, structural, sedimentologic, stratigraphic, and geochronologic information on the Ordovician period at the scale of the Variscan belt of Europe. The project also includes the detailed multidisciplinary study of three key areas of the inner part of the Gondwana margin located in Southern France and Spain and the reexamination of the reference sites in Sardinia.

The present contribution aims at presenting the structure of the database and the progress made at building the magmatic/geochronological sub-base, as well as preliminary fieldwork from Southern France.

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Variscan orogeny in the Pontides, northern Turkey

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The collision of Gondwana and Laurussia in the Late Carboniferous led to the Variscan orogeny in Europe and resulted in the creation of the supercontinent Pangea. In contrast, most of the Asia escaped the collision and continued to face an ocean in the south. The Pontides are located in this transitional region between Carboniferous continental collision in the west and continuing oceanic subduction in the east (Fig. 1). They are characterized by a zone of Early Carboniferous high temperature metamorphism and Late Carboniferous – Permian plutonism, which extends from the Strandja Massif in the Balkans to the Caucasus (Fig. 2). This zone constitutes the eastward extension of the Variscan orogeny in Serbia and Bulgaria. Permo-Carboniferous crystalline rocks form isolated outcrops under the Mesozoic sequences in the Pontides (Fig. 2). Although the outcrops are separated by large distances, they share several common features. In the Sakarya Zone of the Pontides a HT/LP metamorphism characterized by sillimanite-cordierite-garnet bearing assemblages and partial melting is dated at ca. 330 Ma. The metamorphism was followed by the intrusion of Late Carboniferous (330-320 Ma) calc-alkaline granitoids. During the latest Carboniferous there was uplift and erosion, and deposition of Upper Carboniferous (Gzhelian) molasse with thin marine interbeds.

The Variscan events are less clear in the Strandja Massif due to Late Jurassic – Early Cretaceous metamorphism and deformation. Late Carboniferous (315-302 Ma)

granitoids were probably deformed and metamorphosed during the latest Carboniferous (ca. 300 Ma) followed by the intrusion of widespread Permian (294-253 Ma) calc-alkaline granitoids. Lower Triassic continental clastic rocks lie unconformably over the Variscan basement.

The Istanbul Zone of the Pontides is characterized by a well-developed Paleozoic sedimentary succession extending from Ordovician to Carboniferous. In the western part the Paleozoic succession ends with the Visean turbidites, which were deformed but not metamorphosed during the Late Carboniferous. In the eastern part of the Istanbul Zone the Paleozoic succession continues into Upper Carboniferous coal measures followed by folding and uplift. Late Permian (262-255 Ma) granitoids intrude the deformed Paleozoic rocks.

Reconstruction of the Late Paleozoic events in the Pontides is difficult because of the effects of the Cimmeride and Alpine orogenies, which reworked the Variscan units and their contacts. The Istanbul Zone is generally correlated with Avalonia and was probably accreted to the southern margin of Laurasia during the late Ordovician – early Silurian. The Sakarya Zone was probably a Late Paleozoic ensialic arc, which collided with the Istanbul Zone during the Carboniferous. The collision between the arc and the continent and the subsequent crustal thickening was followed by the intrusion of widespread Permian granitoids.

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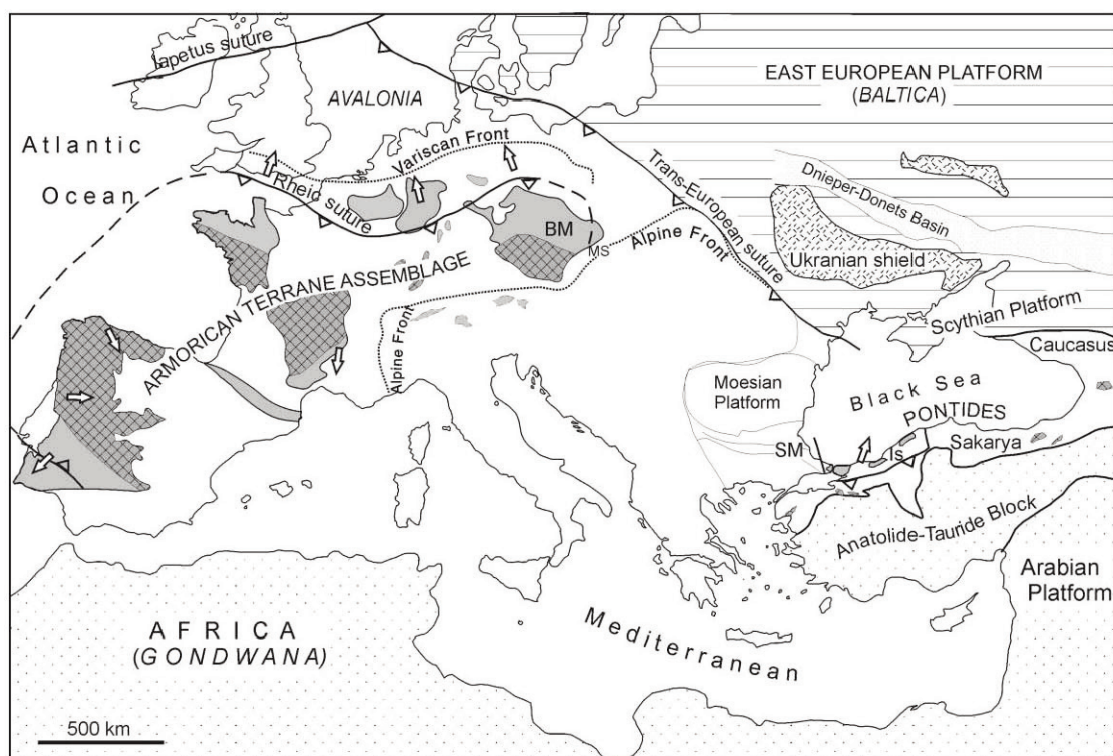


Fig. 1.- Simplified tectonic map of Europe showing the major Variscan units. The hachured pattern indicates regions with medium to high grade Carboniferous metamorphism. The triangles on the sutures indicate subduction polarities and the arrows the vergence of Variscan deformation. BM, Bohemian Massif; MS, Moravo-Silesia; Is, Istanbul Zone; SM, Strandja Massif (modified from Okay et al., 2008).

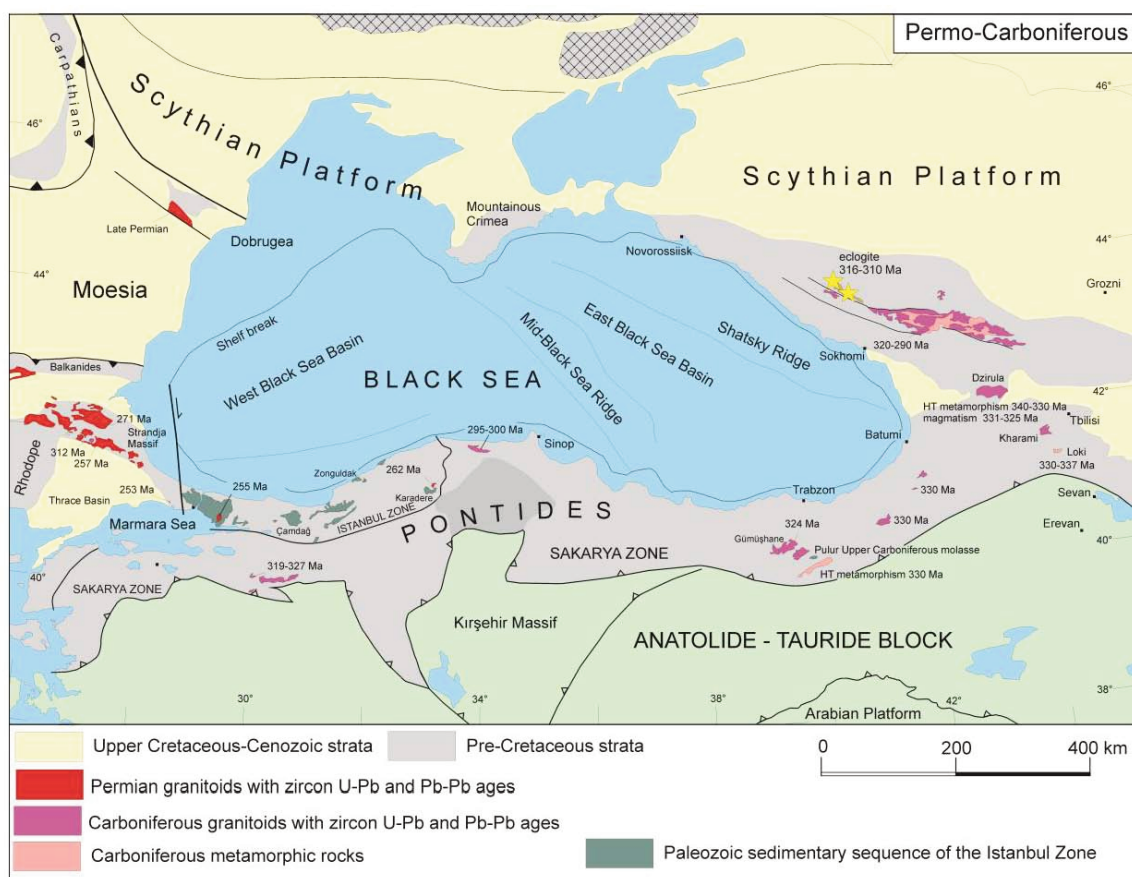


Fig. 2.- Outcrops of Permo-Carboniferous magmatic and metamorphic rocks in the Black Sea region. Also shown are the outcrops of the Paleozoic series in the Istanbul Zone (modified from Okay & Nikishin, 2015).

Figueira de Castelo Rodrigo – Lumbrales Anatectic Complex (Iberia): the role of shearing on exhuming high grade rocks

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The Figueira de Castelo Rodrigo – Lumbrales Anatectic Complex (FCR-LAC) is an association of high grade metamorphic rocks and two-mica granites, having evolved during the variscan orogeny. This anatectic complex is conditioned by the Juzbado-Penalva do Castelo Shear Zone (JPCSZ), a major ENE-WSW sinistral linement in the Central Iberian Zone (CIZ; Iglesias and Ribeiro, 1981), responsible for the inflexion of D1 variscan trend from the dominant NW-SE to E-W, and for the juxtaposition of the FCR-LAC to the low-grade metamorphic rocks (biotite zone).

A petrological and structural analysis was conducted in the Figueira de Castelo Rodrigo region (Portugal), and several sectors were individualized (Fig. 1). The Azêvo and Olmedo de Camaces sectors exhibit D3 shear deformation, though it is still possible to distinguish D1 from D3 structures affecting the Azêvo region. In the Penha de Águia sector is clear the ductile D3 deformation, transposing D1 structures, with shear foliation (N68E, 68°S) and stretching lineations (11°, S68W and 11°, N79E) with sinistral movement criteria. In the Nave Redonda-Almofala sector, the deformation was clearly more fragile, with stretching lineations near dip-slip, compatible with an inverse movement of this shear zone during the late stages of the variscan D3. Up North, the Escalhão sector (Fig. 1) not only exhibit the same sinistral displacement criteria, but also two deformation stages, a more ductile and a later more fragile, conditioning the late-granitic intrusions.

Migmatites present in the FCR-LAC are mainly diatexites and, less frequently, metatexites poor in sillimanite.

Interlayered in the diatexites, some calc-silicate rocks exhibit a paragenesis of quartz - feldspar - hornblende - hedenbergite - garnet. This mineral association was used in thermobarometric calculations using THERMOCALC 3.33 (Holland and Powell, 1998). Modelling of P-T conditions of these rocks resulted in $T = 761 \pm 50$ °C for $P = 5.0 \pm 1$ kbar, conditions that do not correspond to peak metamorphism. For the genesis of the anatectic rocks we propose an episode involving decompression, probably prior to D3. This first exhumation process was followed by a second, responsible for the relation between the anatectic complex and the low-grade suite, due to JPCSZ displacement.

Thereby we propose a D3 evolution model for the FCR-LAC in a simple shear dominated transpression, compatible with the exhumation in between shear bands of the FCR-LAC within a main sinistral movement of the JPCSZ (Fig. 2).

Aknowledgments

This work is a contribution for PETROGEO (LNEG) and Pest Programme (FCT-Pest-UID/GEO/50019/2013). Inês Pereira is thankful for FCT funding SFRH/BGCT/52033/2012.

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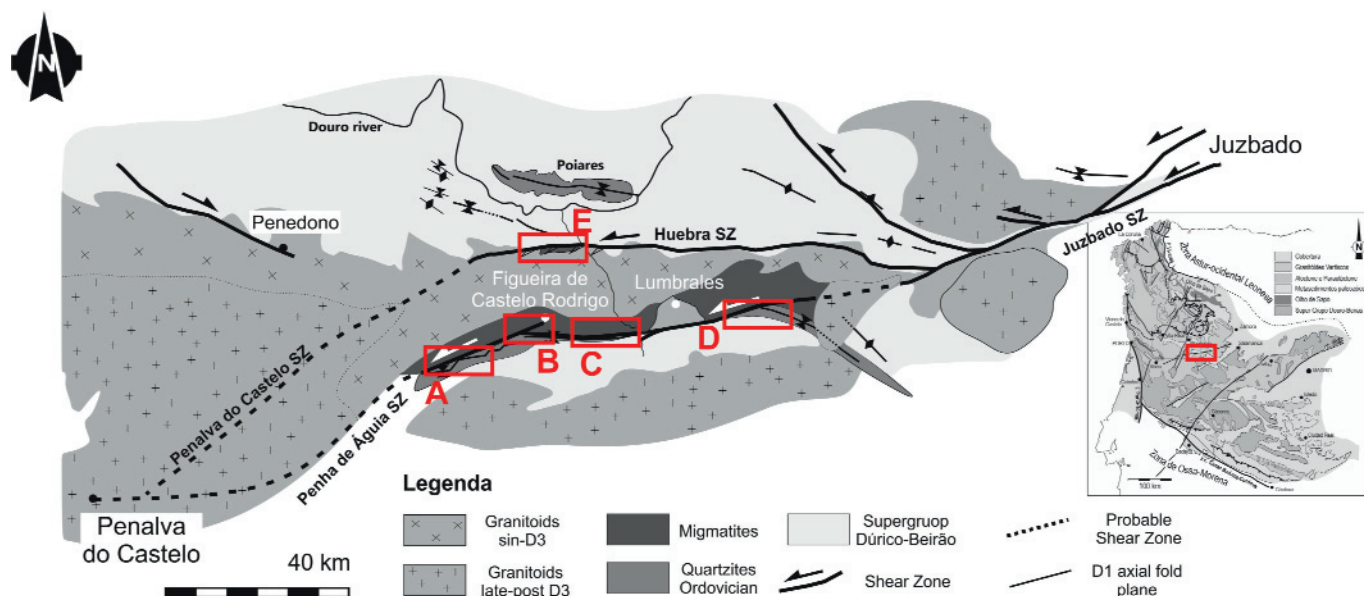


Fig. 1.- Geological Map of the FCR-LAC, with the JPC Shear Zones. Individualized sectors: A- Azêvo, B - Penha de Água, C - Nave Redonda - Almofala, D - Olmedo de Camaces, E- Escalhão.

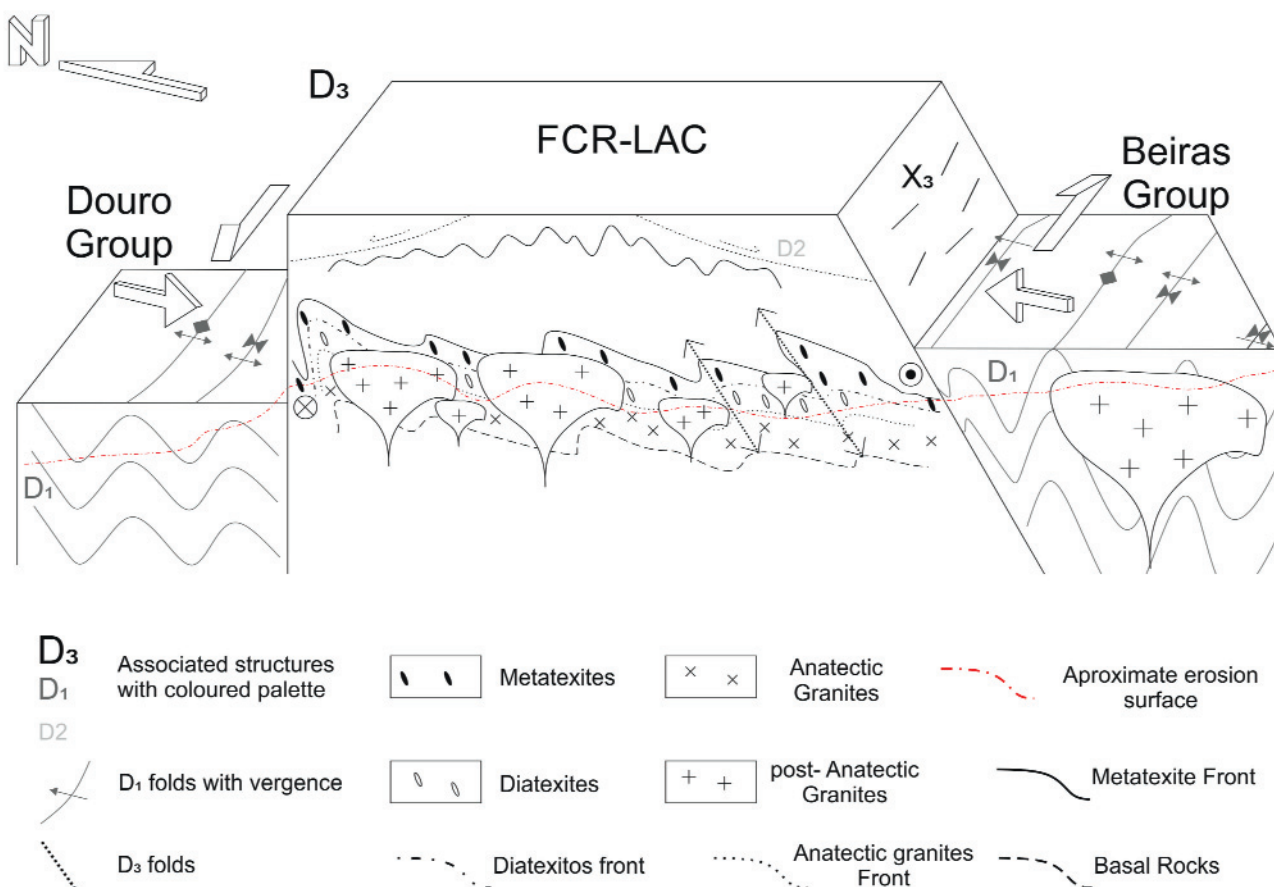


Fig. 2.- Evolution of FCR-LAC and JPCSZ during variscan D3 in a sinistral simple shear dominated transpression.

The effect of rheology on the strain partitioning in the crustal section at the western margin of the Teplá-Barrandian Unit

PEŘESTÝ Vít

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The interplay between rheological properties and localization of deformation was studied along the vertical crustal section exposed at the western margin of the Teplá-Barrandian Unit (TBU). This area is characterized by continuous increase in metamorphic grade from lower-greenschist to amphibolite facies rocks in mid-crustal metasediments and from amphibolite to granulite facies metabasites in the structural footwall. The present day exposure is associated with two early Variscan tectono-metamorphic stages - prograde horizontal shortening D2 and retrograde vertical shortening event D3.

Two principal structural patterns A and B have been recognized in the area. The simple structural pattern A is characterized by N-S trending subvertical foliation S2, while structural pattern B exhibit almost complete transposition of subvertical fabric S2 into gently SE to E dipping foliation S3 forming characteristic S2 girdle. Although the D3 deformation is identified within pattern A, it is generally weaker and exemplified by N-S trending subhorizontal intersection lineation L3. In pattern B, the increase of D3 finite strain intensity is accompanied with rotation of L3 lineation towards D3 stretching direction plunging gently to the E.

In the studied area, the two structural patterns form a sequence ABAB from structural top to structural bottom and the boundaries between domains characterized by A and B patterns correspond to 3 major attachment -

detachment zones: 1) zone of partial attachment corresponding to rheological weakening in the metasediments in the vicinity of staurolite isograd, 2) a sharp detachment driven by rheological contrast between metabasites and partially molten sediments, and 3) a detachment zone between strong melt free metagabbros or amphibolites and weak migmatitic amphibolites with eclogite lenses.

The observed rotation of lineation and formation of S2 girdle from originally subvertical N-S trending S2 foliation have been tested by simple kinematic model and revealed that such structural pattern requires significant simple shear component combined with either a prolate symmetry of D3 deformation tensor or an existence of pre-S2 E-W trending vertical fabric.

We interpret the observed deformation pattern along the studied profile as a continuous transition from mechanically coupled evolution during stage D2 affecting the entire crustal section to mechanically decoupled evolution due to strain localization and partitioning during D3 deformation. We suggest that localization into the mechanically weak zones is primarily caused by thermally and compositionally controlled changes of rheological properties of studied rocks. These weak zones accommodated most of the non-coaxial component of D3 finite strain that resulted in footwall exhumation of deep seated rocks of the western margin of the TBU.

Structural and geochronological advances in the variscan evolution of SW Iberia

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MARTÍNEZ POYATOS David J., SIMANCAS José Fernando, AZOR Antonio

The boundary between the Ossa Morena Zone (OMZ) and the South Portuguese Zone (SPZ) in Southwest Iberia has been classically interpreted as a suture related to the Devonian closure of the Rheic Ocean (Fig. a, b). This boundary is constituted by three units (Fig. c): (i) the Beja-Acebuches Unit (BA unit), a metamafic unit that crops out all along this boundary and has been previously interpreted as a Rheic ophiolite, i.e. a remnant of pre-carboniferous oceanic crust; (ii) the Pulo do Lobo unit, a low grade metasedimentary unit with minor MORB-like metabasalts, thought to be the remnants of a Rheic subduction-related accretionary prism; and (iii) the allochthonous Cubito-Moura unit, which contains high-pressure and ophiolitic-like rocks emplaced onto the Ossa-Morena Zone border. New structural and geochronological data have improved our knowledge on the geometry and timing of deformations affecting these suture-related units. Thus, the high- to low-temperature interplay of folding and ductile shearing that characterizes the deformation of the BA unit has been determined for the first time. Another major advance has been the characterization of the polyphasic deformation of the Pulo do Lobo unit and the meaning of its MORB-like metamafic rocks. In this respect, the dating of the BA unit protoliths at 340 Ma, together with new dating of metabasalts intruded in the Pulo do Lobo unit, forces a new

interpretation of the previously considered suture-related Peramora Mélange. All these new data point to an Early Carboniferous intraorogenic, extensional, magmatic and metamorphic event imposed over the suture zone, which obscured its previous features (Fig. d). The 344 Ma maximum depositional age for the youngest formation of the Pulo do Lobo unit (Santa Iria formation), suggests its deposition during this magmatic stage. Later on, collision was resumed in an oblique (transpressional) left-lateral regime that gave way to frontal (folds and thrusts) and lateral (shear zones and strike-slip faults) structures, with variable pressure-temperature conditions and spatial distribution. In late Carboniferous time, the deformation and metamorphism decrease moving away from the suture to the SPZ, propagating the transpressive evolution (Fig. e).

The evolution of the OMZ-SPZ boundary after the closing of the Rheic Ocean has been quite complex and characterized by two stages of shortening separated by an extensional stage. This Carboniferous tectonic evolution has strongly obliterated the original features of the Rheic suture in SW Iberia, and only some metamafic lithologies included in the Cubito-Moura unit might constitute the possible remnants of pre-Carboniferous Rheic ophiolitic-featured rocks. As a consequence, the Rheic suture in SW Iberia has an obscure, nearly cryptic appearance.

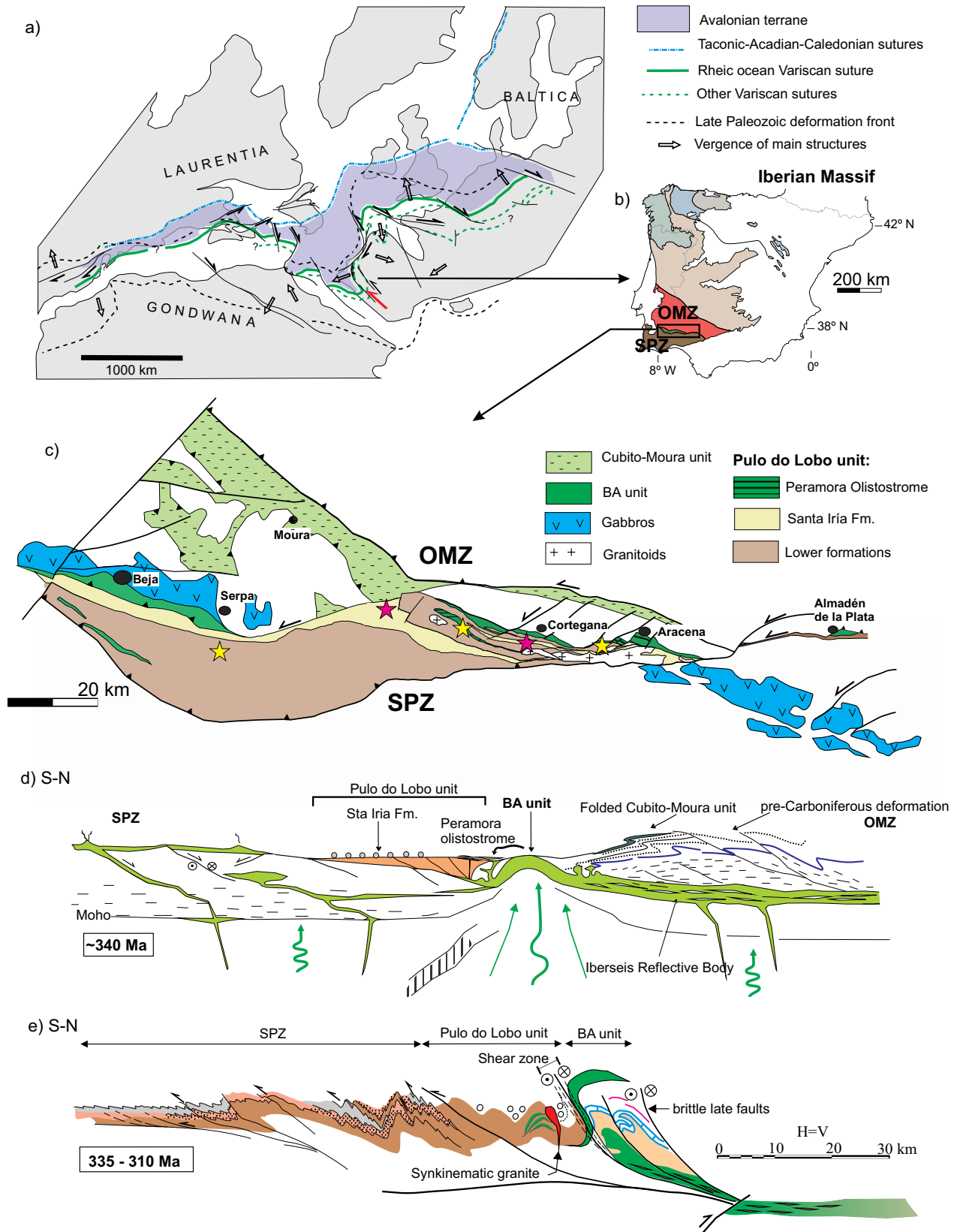


Figure: (a) Reconstruction of the Variscan-Alleghanian orogenic frame at Late Carboniferous time. The Avalonian continental fragment and the inferred Rheic Ocean and other second-order Variscan sutures are depicted. The SW Iberian (Rheic?) suture is highlighted in red. (b) Geological subdivision of the Iberian Massif. OMZ: Ossa-Morena Zone; SPZ: South Portuguese Zone. (c) Schematic map of the OMZ/SPZ boundary showing the different units involved in the suture. Igneous samples (yellow asterisks) and detrital samples (pink asterisks) used for geochronology are located. (d) Sketch showing the early Carboniferous transtensional stage in SW Iberia. The BA unit formed as a proto-oceanic corridor located at the OMZ/SPZ boundary. Other suture-related units are represented. (e) Cross-section along SW Iberia from the suture along the SPZ in Late Carboniferous time.

Geographical and lithological relationships between high-density magnetic lithologies and Variscan Sb ± Au mineralizations in the Armorican belt (France)

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Antimony mineralizations from the Armorican Massif constitute the most important resource for this metal in the French Variscan belt. This type of mineralization is also frequently associated with gold. Most of the Sb ± Au deposits in the Armorican belt consist of stibnite-bearing quartz lodes which are mainly spatially associated with major shear zones (Chauris and Marcoux 1994). These mineralizations are interpreted as being related to a large-scale, late Variscan hydrothermal mineralizing event (Bouchot *et al.*, 2005). In spite of numerous works, geological controls of these different mineralizations still remain unclear. Here we develop a new approach using GIS, geophysical data and mapping data to analyse potential correlations between mineralizations and geological features, like intrusive magmas or lavas, lithologies, or major faults. First we performed a statistical analysis focussed on the quantification of spatial relationships between peculiar geophysical signatures and Sb-occurrence. In order to detect potential links between geophysical anomalies and deposits, we then statistically compared the distributions of geophysical anomaly values near Sb-deposits with the ones for the entire Armorican Massif considered as a reference (Fig. 1A and B). Then a statistical analysis was performed to examine geographical relationships between Sb-deposits and several geological objects (Fig. 1C and D). Main results of our statistical analysis (Fig. 2) show that (i) Sb-occurrences appear spatially associated with local high-density and magnetic zones, (ii) approximately 55 % of Sb-deposits are located at less than 5 km from high density and magnetic zones;

whereas only 35 % of reference points are closer than 5 km from these zones, (iii) where Sb-deposits are farther than 5 km of these zones, 76 % of them are less than 5 km of major faults. Considering associations of high-density signature and relatively high magnetic susceptibility, only basic rocks or iron-mineral deposits (like pyrrhotite-bearing VMS or magnetite-bearing deposits) are possible source candidates for the geophysical anomalies. On the other hand, numerous basic rocks like sill/dyke of dolerite are geographically close from some Sb-mineralization. A promising working hypothesis is that the high-density magnetic zones associated with mineralization are related to basic rocks localized in depth, probably in the upper part of the continental crust, feeding overlying intrusive dykes and sills. Nevertheless the origin of such spatial links must be further analysed. It is possible that basic rocks played a thermal role in the mobility of Sb-rich fluids or a leaching role in the composition of Sb-rich fluids. Several additional studies will be performed on the geochemistry and geochronology on basic rocks samples, especially dolerites.

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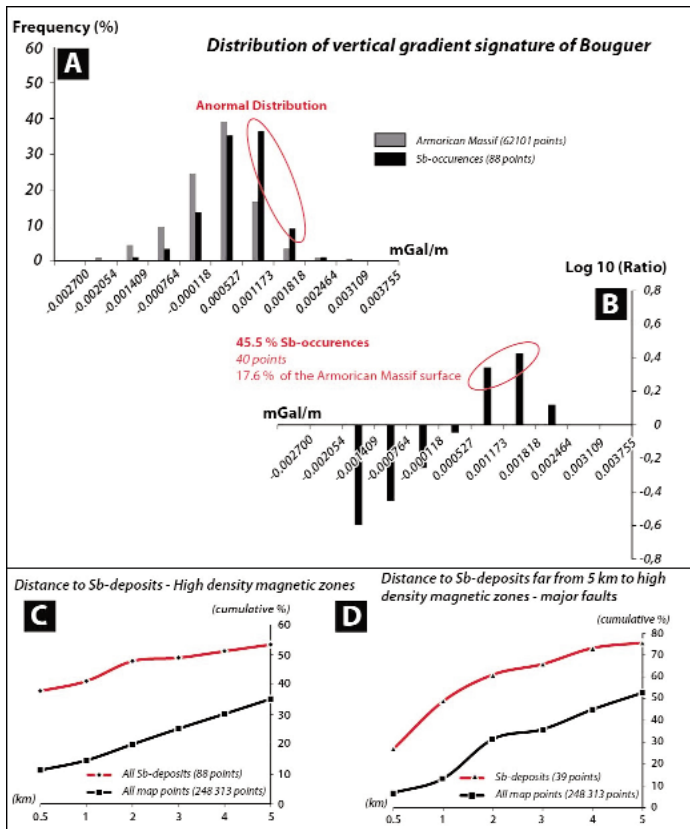


Fig. 1 A.- Frequency histogram of vertical gradient of Bouguer anomaly signature. B) Frequency log₁₀ (Sb-values/Armorican Massif-values) histograms. C) Spatial proximity analysis calculated among Sb-deposits and all map points and high density magnetic zones. D) Spatial proximity analysis calculated among Sb-deposits located at more than 5 km to high-density magnetic zones and to all map points and major faults.

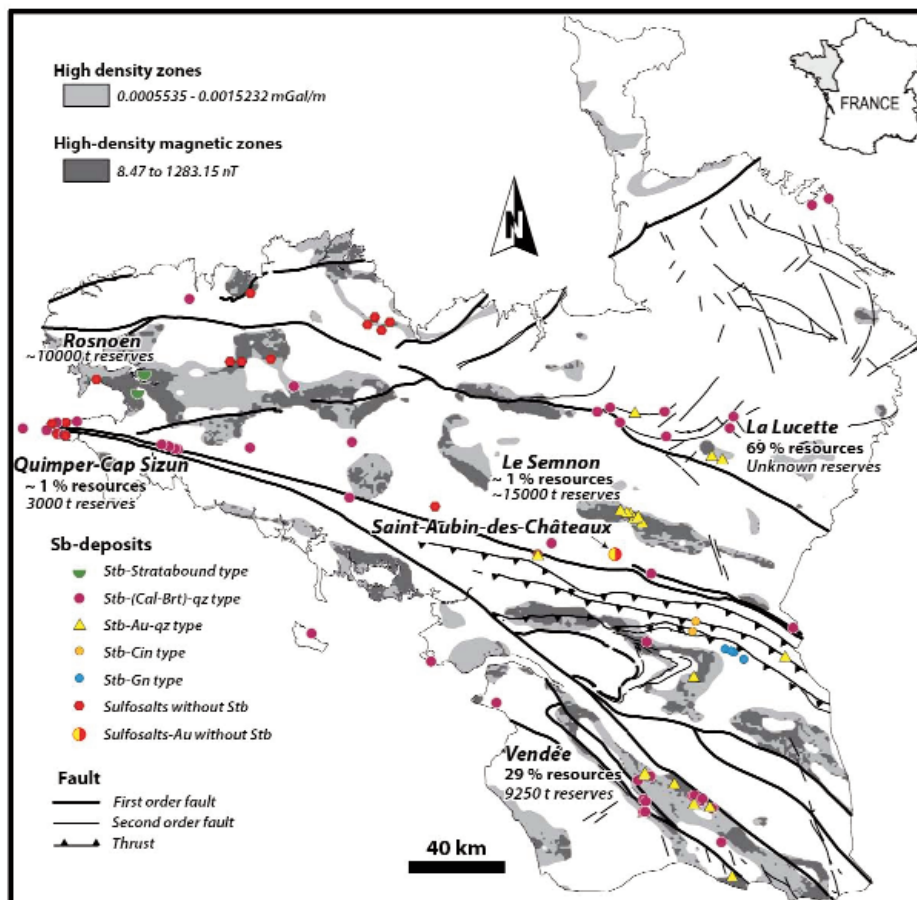


Fig. 2. Map of spatial relationships between new classification of Sb-deposits and high-density and magnetic zones throughout the Variscan Armorican belt. High density magnetic zones have the same range of gravimetric values as high density gravimetric zones. Stb = stibnite, Cal = calcite, Brt = barite, Au = gold, Cin = cinnabar, Gn = galena.

Petrology and age-dating of a Variscan garnet-bearing micaschist from the northern Fichtelgebirge, Germany

RAHIMI Gelareh ¹
 MASSONNE Hans-Joachim

The Saxothuringian area between the Münchberg Massif, where gneisses enveloping eclogite bodies dominate, and the late Carboniferous granites of the Fichtelgebirge is characterized by poorly exposed rocks of low metamorphic grade (Fig. 1). As the P-T evolution of these rocks, mainly psammopelites assigned to a Cambrian to Devonian sequence of Thuringian type, is unknown, we started to study them. In the southeasternmost part of our study area, we detected garnet-bearing micaschists north of the town of Selb. As this medium-grade rock did not fit the general idea of a low-grade metamorphic event in the entire study area, it was studied in detail to derive its P-T path. The micaschist contains mainly quartz, plagioclase, muscovite, chlorite, biotite, and several-mm sized subhedral-euhedral garnets which are characterized by a foam structure in quartz with garnet plates forming an S in favourable sections. According to a study with the electron microprobe (EMP), these garnet porphyroblasts show a prograde concentric zonation from core to rim. For instance, the pyrope component of these garnets increases from 1 to 6 mol%. Potassic white mica shows a compositional range from 3.00-3.13 Si per formula unit. The highest Si contents together with relatively high Mg contents were observed in cores of mica flakes according to X-ray maps obtained with the EMP. P-T pseudosections were calculated for the pelitic bulk-rock composition of the micaschist using the PERPLE_X computer software package, the metamorphic data set by Holland and Powell (1998), solid-solution models for various mineral phases, and a haplogranitic melt model. The P-T pseudosections were contoured by various parameters such as the modal content of garnet and the pyrope content of this phase (Fig. 2). From the contouring of the pseudosection P-T conditions of 9-10 kbar and 535 °C were derived for an early metamorphic stage which was followed by a pressure release to 5.5 kbar

and 550 °C. The final metamorphic P-T conditions recorded by the studied rock are around 3.5 kbar and 580 °C compatible with the presence of some staurolite and andalusite and the absence of melt. To understand the timing of this P-T evolution, U-Th-Pb dating was performed on different monazite grains with the EMP. A more or less continuous age spectrum between 360 and 270 Ma was obtained (Fig. 3). Data of chemical parameters, which resulted from 39 monazite analyses, plotted versus the determined age, demonstrate that with increasing monazite age the La/Gd ratio slightly decreases and the Y content increases. We conclude that at the oldest ages no garnet was present in the rock. Later on, but still in the Tournaisian, metamorphism close to 10 kbar occurred being the result of the collision of Laurussia and Gondwana. This collision caused significant crustal thickening. The subsequent exhumation probably due to erosion of the thickened crust might have occurred in Viséan to late Carboniferous times. Afterwards, a contact metamorphism at 3.5 kbar and subsequent fluid-mediated processes took place, triggered by the intrusion of adjacent granitic magmas at the Permian-Carboniferous boundary (Siebel *et al.*, 2010). Younger monazite ages (<280 Ma) might reflect hydrothermal processes in the Fichtelgebirge area.

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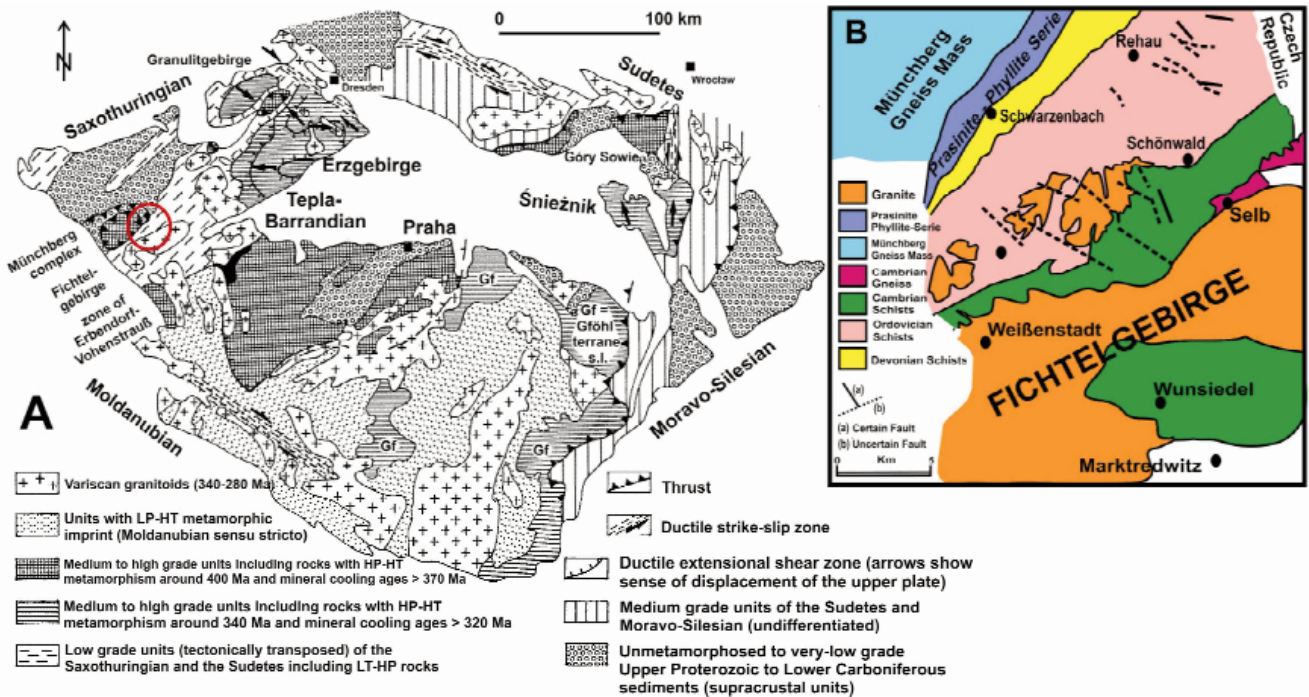


Fig. 1.- Simplified geological map of the Bohemian Massif (A, from Willner et al., 2000) and the study area and its surrounding (B). The circled area in A denotes the position of the study area.

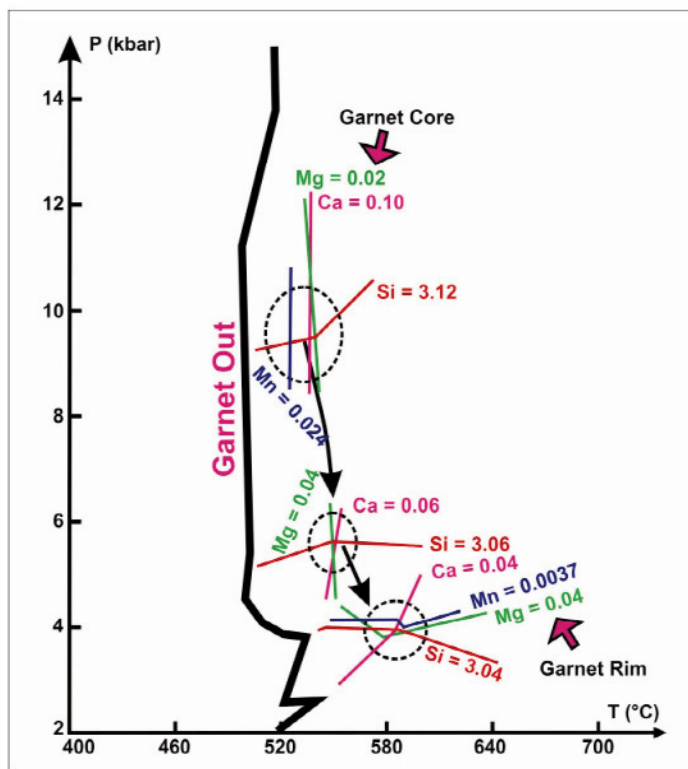


Fig. 2.- P-T path (see black arrows) for the studied rock derived on the basis of the modal content of garnet, the pyrope, grossular and spessartine contents of this phase, and the Si content of potassic white mica.

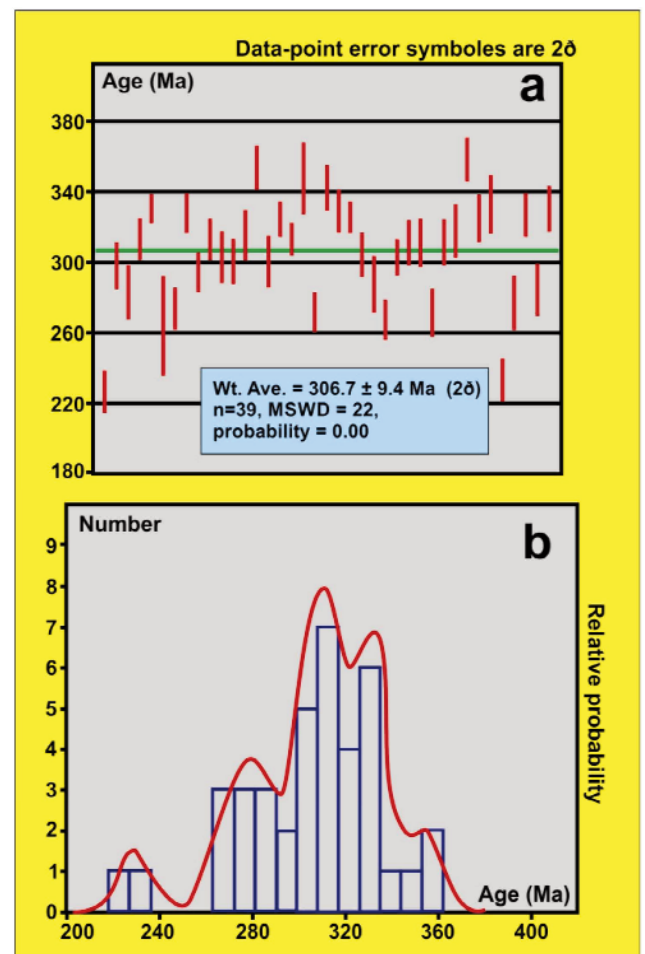


Fig. 3.- Age data evaluated with Isoplot7Ex, ver. 3 (Ludwig, 2003) (a) Linearized probability plot displaying the 39 EMP spot analyses performed on several monazite grains. (b) Probability density histogram of the age data. Different age peaks (red line) are discernable in the histogram.

Effects of mantle hydration and viscous heating on the dynamics of mantle wedge in a subduction system: differences and similarities of 2D model predictions with examples from the Variscan crust

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Mechanisms that favor the exhumation of subducted crustal material, both continental and oceanic, have been explored by means of several models and 2D numerical studies. Petrological and numerical models (e.g. Ernst and Liou, 2008; Roda *et al.*, 2010; Regorda *et al.*, 2013 and refs. therein) reveal that the dehydration process of the oceanic slab, with a consequent hydration of the mantle wedge, have a primary role for developing a convective dynamics in the area between the slab and the upper plate, since the beginning of the subduction.

The geodynamics of a convergent ocean/continent margin, evolving from subduction to continental collision, was analyzed by means of a 2D finite element thermo-mechanical model, in which the physics of the crust-mantle system is described by the equations for continuity, conservation of momentum and conservation of energy. A viscous behavior for the whole system is assumed, with both density and viscosity depending on temperature and composition. Different values of convergence velocities, 3, 5 and 8 cm/yr, have been used, as representative of slow, medium and fast subduction systems, respectively.

Our analysis is particularly focused on the effects of viscous heating and mantle hydration on the dynamics in the wedge area. The results support that these mechanisms, differently from our reference model without hydration and

viscous heating (Marotta and Spalla, 2007), induce the development of short wavelength convective cells in the wedge area, that favor the exhumation of buried crustal material since the early stages of the subduction (Fig. 1).

Model predictions, in terms of pressure, temperature, lithology and time, will be compared with structural, petrological and age natural data from the European Variscan crust to check and interactively improve 2D numerical models of the explored ocean/continent subduction system.

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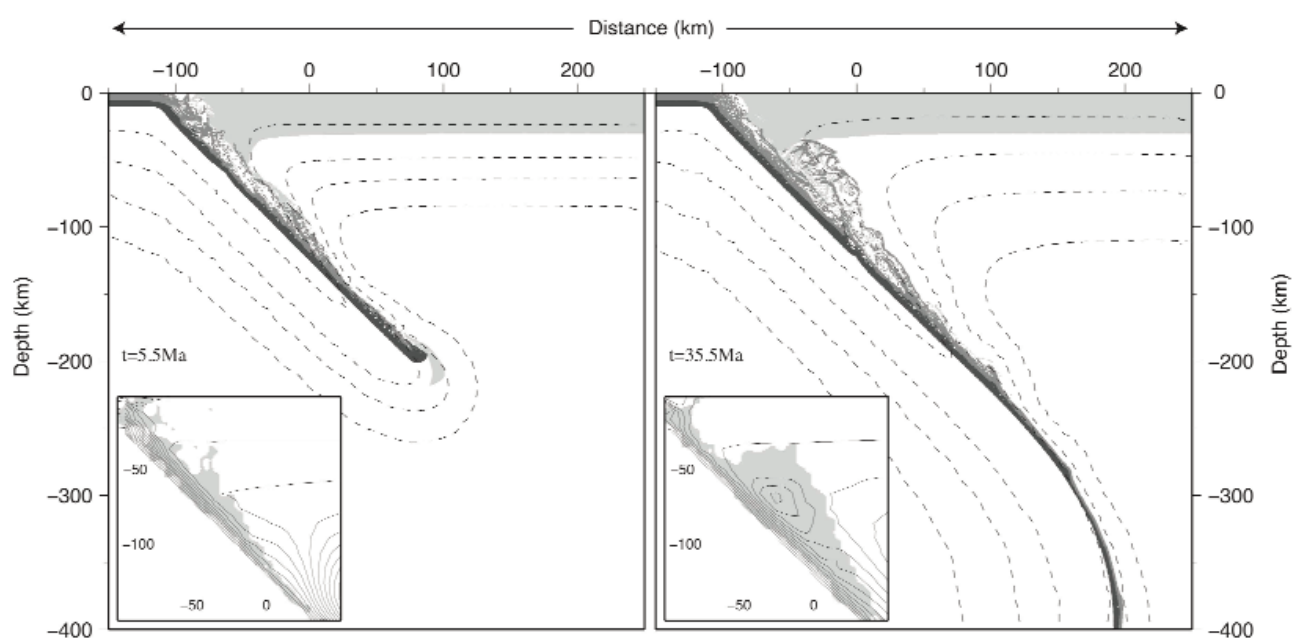


Fig. 1.- Two evolutionary stages of the model. Dashed black lines indicate 800 K, 1100 K, 1300 K and 1500 K isotherms. Black, dark gray and light gray points represent lower oceanic crust, upper oceanic crust and continental crust, respectively. In the insets, the streamlines (black lines) and the hydrated area (light gray) are also represented.

Geological and petrological constraints on the variscan evolution of the NW area of Port-Viseu Belt

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AREIAS M., FERREIRA J.², MARTINS H.¹, SANT'OVAIA H.¹

The Porto–Viseu Belt, located in Central Iberian Zone (CIZ), is a variscan structure, with syntectonic anatectic granites in the core, associated with HT-LP migmatites: the Mindelo Migmatic Complex (MMC) at north of Porto [1], The Mundão Anatectic Complex (MAC) near Viseu [2], the Pedregal Granite (PG) and associated migmatites [3] at east Porto and the Madalena–Lavadores Migmatites (MLM) at south of Douro River (Fig. 1).

In the NW sector of Porto-Viseu Belt, towards both side of this antiformal structure the metamorphism is recorded in pelitic and semi-pelitic with some calc-silicate rocks, assigned to the Schist-Greywacke Complex (SGC) in NE flank and to Lourosa Unit (LU) in SW flank. SGC is attributed to CIZ and LU to Ossa Morena Zone (OMZ) being the limit between the two zones materialized by the Porto-Tomar Shear Zone (PTSZ). The PTSZ is considered the boundary between the OMZ and CIZ and more recently the boundary between the CIZ and the Finisterra Terrane [4]. According to other authors PTSZ is a late variscan strike-slip shear zone [5].

Late LP-HT metamorphism is evident at both side of this megastructure, with syntectonic anatectic granites in the core, in geometric continuity with Lavadores post-tectonic biotitic granite. The metamorphic grade decreases quick and gradually from sillimanite (kyatine) and staurolite zones to biotite and chlorite zones materializing a field gradient with condensed isogrades parallel to the granite bodies associated with migmatites. In both side of the structure the migmatitic complexes (MMC and PG at N and NE and MLM at SW) are represented by the association of diatexites and metatexites with rounded resisters of greywacke and calc-silicate rocks. These resisters are well represented in MMC but they are also present in MLM, although more sporadic (Fig. 2). Both, the metapelites and

diatexites of MLM show the presence of Zn-rich hercynite, always associated with sillimanite and magnetite. Hercynite is also present in PG, considered a secondary diatexite, as a result of a second phase of crustal partial melting in prograde conditions. This association and the abundance of magnetite in metapelites, highlighted by the high values of Magnetic Susceptibility and magnetization curves of Isothermal Remnant, points to the correlation of these lithologies with the SGC. The reference to occurrence of hercynite in Torredeita (Viseu) and of residual staurolite in pelitic rocks associated with metatexites and diatexites, should be noted. Staurolite may be the direct precursor of Zn-rich hercynite, since in prograde metamorphic conditions staurolite progressively concentrate Zn.

Taking into account the similar lithology and tectonic-metamorphic variscan evolution in both side of NW area of Port-Viseu Belt there is no evidence for considering an exotic terrane in the western sector of this thermal dome. The dextral shear deformation is more intense at western, but is also expressed in the eastern board, with a dominant NW-SE trend and a SW dip. At western a later dextral brittle shear zone with N-S to NNW-SSE trend has an evident geomorphological expression.

Acknowledgements

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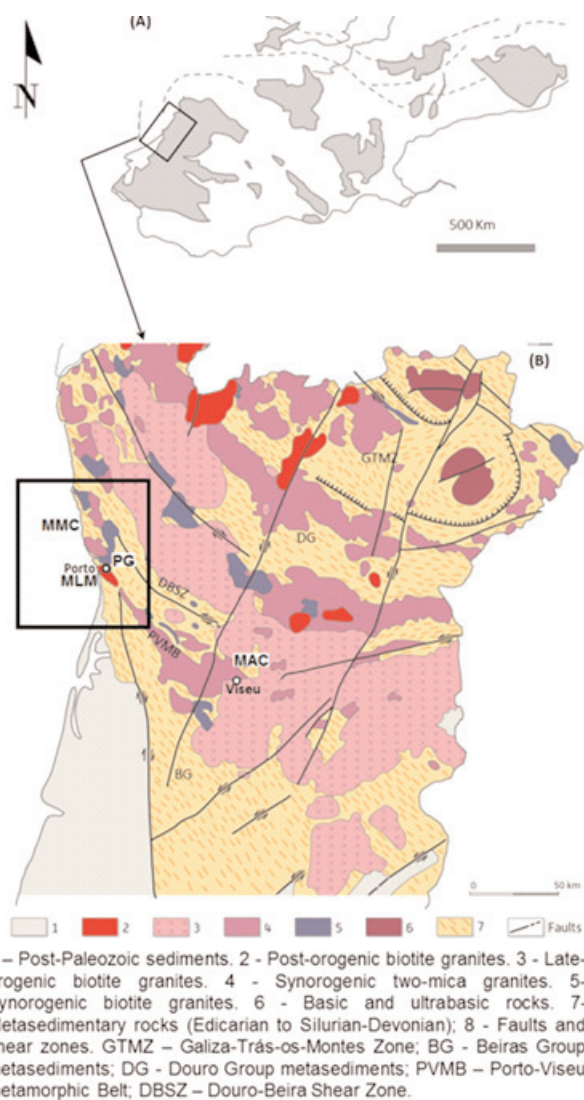


Fig. 1.- Geological sketch and location of the studied area. (A) European Variscan massifs; (B) Simplified geological map of northern Portugal. MMC-Migmatite Mindelo Complex; PG-Pedregal Granite; MLM-Madalena Lavadores Migmatites; MAC-Mundão Anatectic Complex.

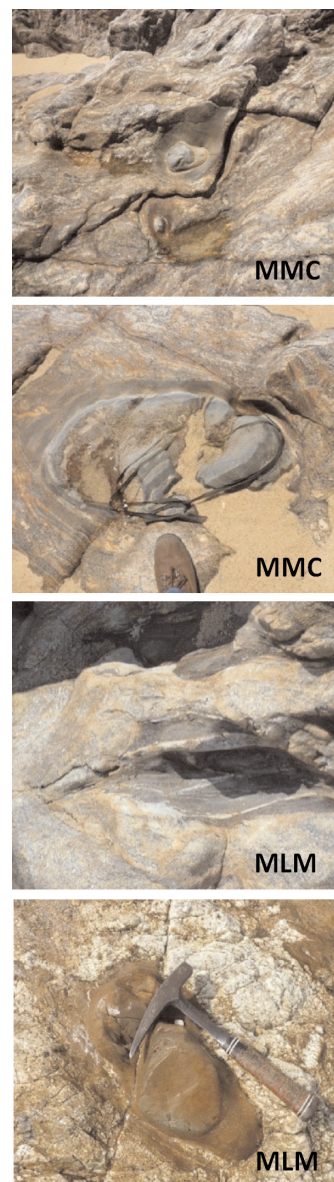


Fig 2.- Field photographs of calc-silicate and greywacke resisters in MMC (top images) and in MLM (bottom images).

Chemical character of Variscan granites of the Saxo-Thuringian Zone

ROMER Rolf L.¹

KRONER Uwe²

The Saxo-Thuringian Zone includes an Autochthonous Domain that was little affected by the Variscan orogeny and an Allochthonous Domain that includes Variscan high-strain and high-grade rocks. The two domains became juxtaposed against each other during the final stages of the Variscan orogeny along the Wrench-and-Thrust Zone. All three structural elements include the same lithologies. The voluminously most important units are the Cadomian basement (a former magmatic arc) and Sn-W enriched Ordovician sedimentary rocks and their metamorphic equivalents. Late Variscan and post-Variscan magmatism in the Saxo-Thuringian Zone largely is related to the emplacement of the Allochthonous Domain (338-333 Ma), crustal melting within the Allochthonous Domain (327-318 Ma), and repeated post-Variscan extensional reactivation of older structural elements (305-275 Ma) within the orogenic foreland (Autochthonous Domain) and to a lesser extent in the Allochthonous Domain. This magmatism occur in different tectonic settings and in part tapped different sources. Therefore, granites within the Saxo-Thuringian Zone allows to elucidate the relation between (i) source enrichment, (ii) sedimentary and tectonic accumulation of Sn-enriched source rocks, and (iii) the heat source for the development of Sn-specific granites and possible Sn mineralization.

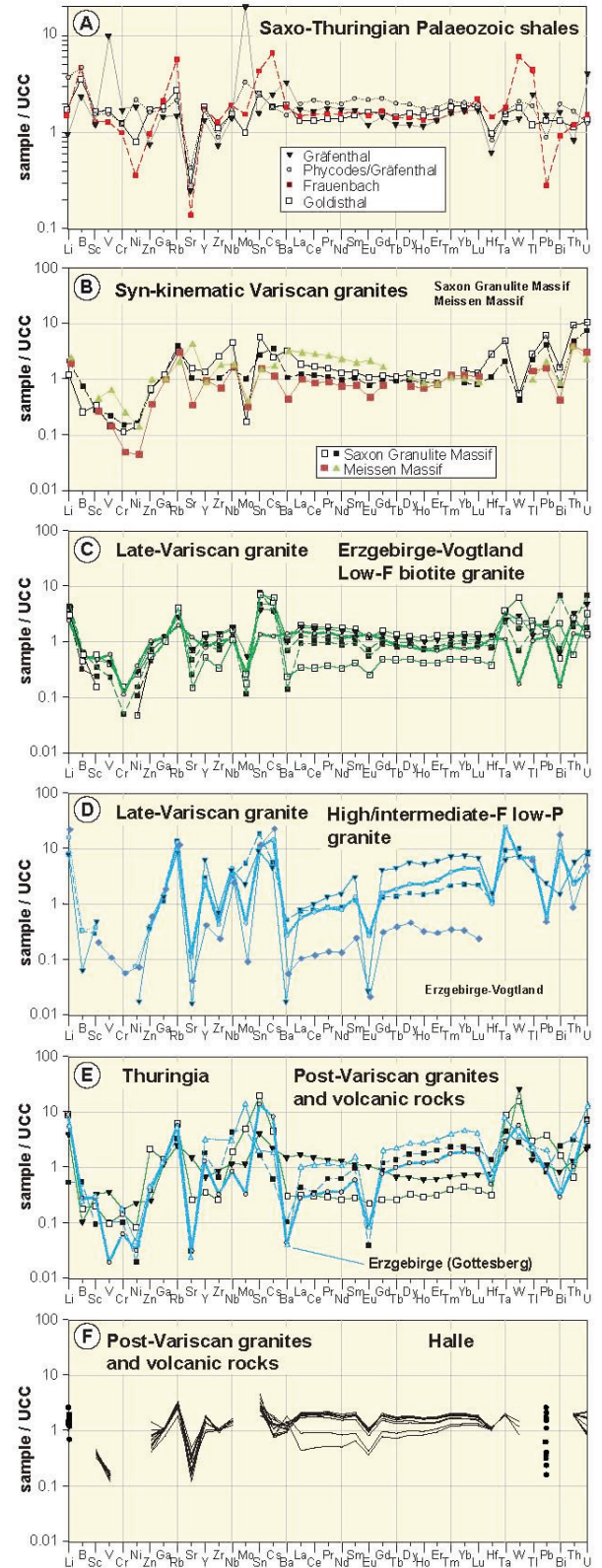
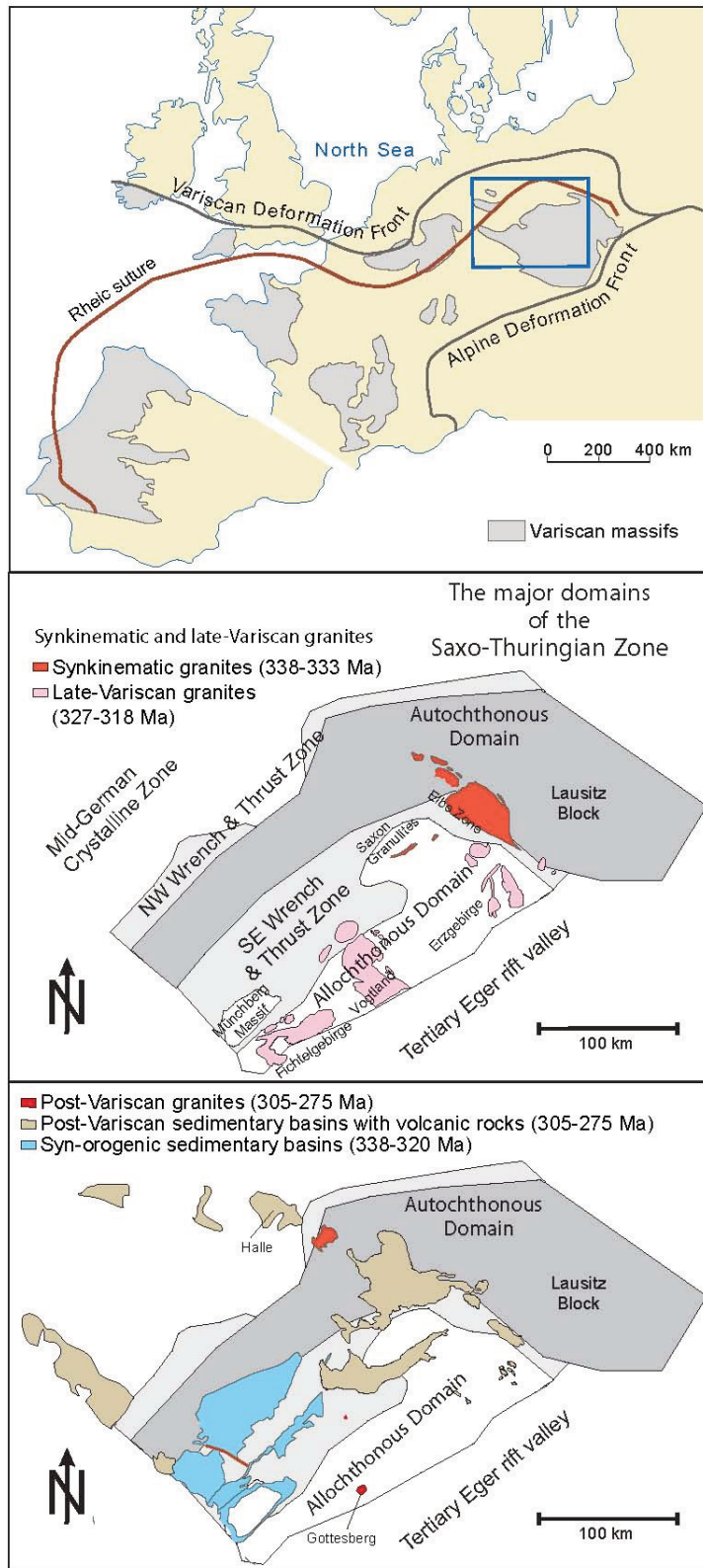
The 338-333 Ma old intrusions include mantle-derived material or formed in contact with the ultrahigh-temperature Saxon granulites. They did not involve Sn-W enriched Ordovician sedimentary rocks. They do not show Sn-enrichment or other geochemical fingerprints distinctive for Sn-specific granites. The 327-318 Ma old granites of the Allochthonous Domain are crustal melts with I-, A-, and S-type affinity and fall in two different geochemical groups

depending on source rocks. The first group has flat Upper Continental Crust (UCC)-normalized pattern, shows a weak anomaly in Sn, Cs, and Li, but has no associated mineralization. The second group has UCC-normalized pattern with distinct enrichment in Sn, W, Nb, Ta, and depletion in Sr, Ba, and Eu even in the least evolved granites. These granites typically show associated Sn mineralization. The 305-275 Ma old granites have I- and S-type affinity and show the same chemical pattern as the 327-318 Ma old granites of the Erzgebirge. Flat UCC-normalized pattern are found in granites from Thuringia and the rhyolitic volcanic and subvolcanic rocks in the foreland of the Variscan orogen. They all have slightly enhanced Sn contents, but no mineralization. Granites of the second group of the 305-275 Ma old granites resemble the 325-318 Ma old Sn-specific granites of the Erzgebirge and occur in Thuringia and the Erzgebirge, where they show associated mineralization.

The contrasting chemical signature of the granites is inherited from the crustal source rocks: (i) the volcanic rocks of the Variscan foreland have an arc signature, even though they post-date subduction by more than 40 Ma. (ii) Enhanced Sn contents occur only in areas where Ordovician sedimentary rocks significantly contributed to the melts. Mineralization occurs only in areas with extensive tectonic stacking of Ordovician Sn-enriched sedimentary rocks and heat sources that allow for high-temperature melting and, therefore, is restricted to the Allochthonous Domain. Mineralization is particularly well developed in the Erzgebirge as thick packages of Sn-enriched sedimentary rocks have been extensively stacked during the Variscan orogeny and the emplacement of UHT rocks provided the heat for crustal melting.

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Metamorphic records of partial subduction and continental collision in and around the parautochthon of the NW Iberian Massif

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The parautochthonous domains of the Variscan Orogen represent paleogeographic and geodynamic intermediate pieces of a large thrust pile that separates the autochthon from an upper set of allochthonous terranes and ophiolites representing a suture zone. In contrast to the early subduction-related HP metamorphism that affected some of the allochthonous units, the parautochthonous and autochthonous domains are commonly thought to have not been involved in the continental subduction process, their imprints of intermediate to LP metamorphism being related to subsequent collisional tectonics. New data from the NW of the Iberian Massif (Fig. 1a), point to a more complex scenario in which at least part of the parautochthonous section experienced HP/L-IT conditions before the onset of Barrovian metamorphism. Moreover, some sections of the autochthon immediately beneath the parautochthonous nappes also preserve evidences for an initial P/T gradient higher than classical Barrovian.

The Upper Parautochthonous nappe beneath the allochthonous complexes of Cabo Ortegal and Órdenes is mostly formed by pelitic and semipelitic schists, which may contain albite porphyroblasts trapping tiny aligned inclusions of Qz, Tur, Rt, Ilm and rare white mica (WM). These minerals define an internal schistosity (S_i) that can vary from previous to equivalent to the main external schistosity (S_e). Both, WM from S_i and matrix micas crenulated by S_e , show high silica contents and mineral chemistry compatible with HP/L-IT metamorphic conditions. Combined Massonne and Schreyer (1987) Si-in-phengite geobarometer and PI-Ms geothermometer (Green and Usdansky, 1986) suggest P_{min} conditions = 11-14 kbar and $T = 450-500$ °C for the early metamorphic recrystallization of these rocks (1, 2 in Fig. 1b). No HP/L-IT relics have been found in the rest of the Upper Parautochthonous nappes or in the Lower Parautochthon.

On the contrary, THERMOCALC (Powell and Holland, 1988) average P-T estimations of the Barrovian assemblage Grt + Bt + Pl + Ms + AIS + Rt + Ilm on pelitic schists from the Lower Parautochthonous nappe affected by the extensional Arnoia Detachment (Celanova Dome), yield prograde conditions around 7.5 Kbar and 600-700 °C (fields 3c-Grt center, 3r-Grt rim in Fig. 1b; 4c-Grt center, 4r-Grt rim for the retrograde evolution of the detachment), which are lower in P and considerably higher in T than the former HP/L-IT conditions.

In the autochthons of the Sanabria region, Ky-bearing slates and veins also show low-T assemblages with high-silica WM, Chl, Rt, Il and Ap (Bt- and Pl-free). The Massonne and Schreyer (1987) barometer yields P_{min} of 9.0 kbar for temperatures that can not be too much higher than the pyrophyllite = Ky + Qz + H₂O reaction, proceeding at 425-450 °C (field 5 in Fig. 1b). On the other hand, THERMOCALC average P-T analyses on Early Ordovician schists from the Villadepera Antiform displaying Grt + Bt + Pl + Ms + AIS + Rt + Ilm, give conditions near 11-12 kbar and 700-725 °C (6c-Grt center, 6r-Grt rim, Fig. 1b). Such conditions are markedly higher in T than those above of the Ky-bearing rocks, and match those registered by correlative rocks from central Iberia (paths A and B in Fig. 1b).

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Fig. 1a - Geological sketch of the Parautochthonous Domain in the NW Iberian Massif. C: Celanova Dome, CO: Cabo Ortegal Complex, M: Morais Complex, S: Sanabria Antiform, SD: Schistose Domain of central Galicia, O: Órdenes Complex, V: Villadepena Antiform. b) Thermobarometric results and P-T paths.

The structural control of the tin mineralisation at the Bou El Jaj project (NE of the central Hercynian massive)

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Bou El Jaj (BLJ) sector is in the NE part of the Hercynian Central Massif, about 60 km south of Meknès city, along the NE extension of the Smaala Oulmes shear zone, limiting the Khouribga-Oulmès Anticlinorium to the West and the Fourhal-Tel Synclinorium to the East.

The main rock unit out cropping at Bou El Jaj includes Upper Palaeozoic turbidites (Upper Visean-Namurean) cross cut by intrusive bodies (Rhyolite and monzo-diorites dykes and sills) trending parallel to the sedimentary bedding structures. The NNE trending tourmaline altered sediment corridor is parallel to the regional shear zone orientation. It stretches over 8km from Bou El Jaj, materializing its SSW tip, to the Achmmach Tin Project located at the NNE end of the corridor (Achmmach is one of the biggest Tin deposit in the world that have same mineralisation style as BLJ).

The tourmaline alteration shows a sharp boundary with unaltered sediments and appears to be controlled by structures such as bedding, dominant cleavage, thrusts and joints.

The sedimentary sequence is deformed by three ductile deformation phases:

D1 is characterised by metric to decametric chevron folds verging to the SE and affecting the entire sequence. This deformation is associated with the development of an axial plane foliation (S1);

D2 produced localised folding short limb with thick hinge and thin limbs;

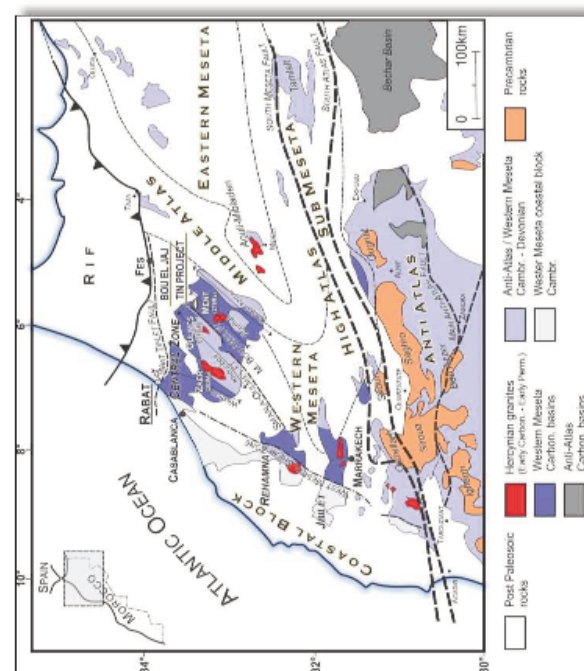
D3 is characterised by gentle undulation of bedding with sub-horizontal fold axial planes. The fault planes dipping to the NW show a generalised reverse kinematic and have been interpreted as SE verging thrusts.

The generalised geological setting at BLJ can be described as that of a fold-and-thrust belt.

The tin mineralised structures are nearly parallel to the stratification and generally oriented N35/063NW. The tin mineralisation occurs as cassiterite and is hosted in quartz veins preferentially associated with tourmaline altered sediments. The quartz cassiterite veins are also found along shear zones N070 oriented moderately dipping to the NNW and occasionally displaying metrics scale pull-apart openings.

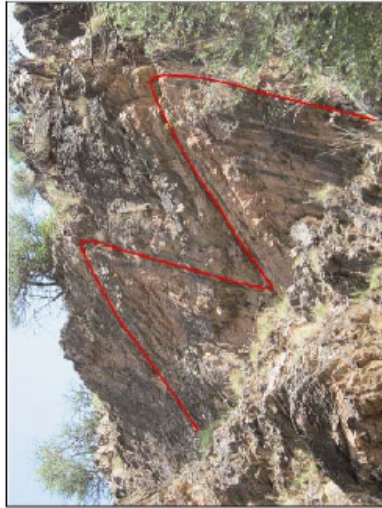
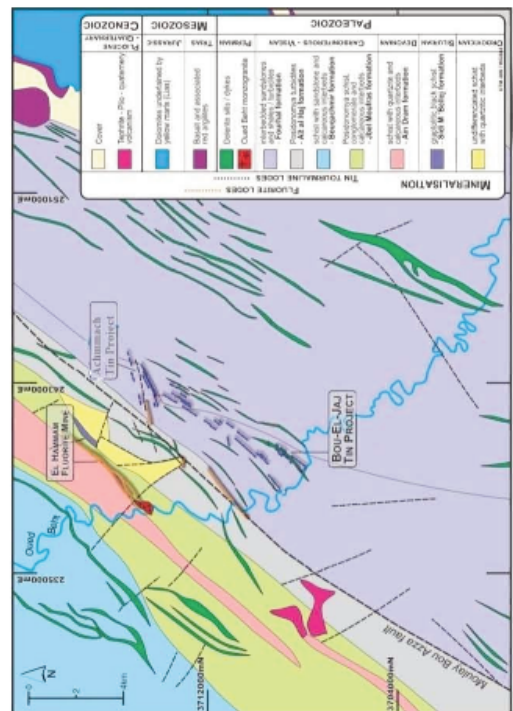
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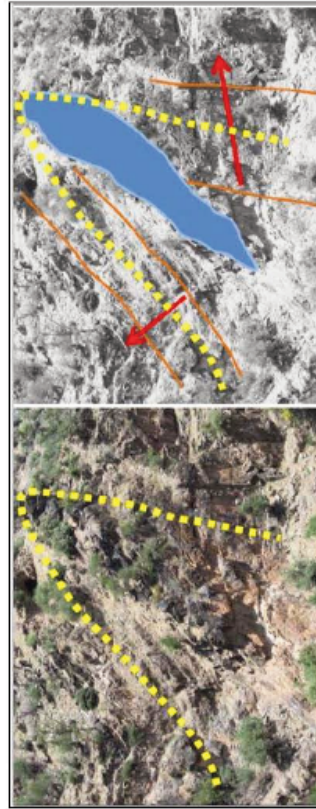


Localisation of the BLJ Tin project on the Moroccan geological map

Regional geological map of the BLJ- Achmmach tourmaline corridor



Chevron folds of D1 deformation phase



Tourmaline alteration occupying the axial plan fold

Tourmaline alteration occurs in the hinge of short limb fold



Tourmaline in pull-apart structure



I - Type tonalite Evolution: new isotopic and geochronological ICP-MS/TIMS data interpretation from the Central Western Carpathians, Slovakia

SIMAN Pavol¹
HIRATA Takafumi²

The Variscan evolution of the Western Carpathians basement is quite well documented in typical composite granitoid plutons and is still recognizable within the Alpine tectonics and regional reworking. Variscan granitoids and orthogneiss form a miscellaneous cluster of rocks with differ age, origin and tectonic position.

The Vepor pluton (Slovenské Rudohorie Mts.) occupies a central part of the Western Carpathians domain, intruded into high to medium - grade metamorphites, partly overthrust and often deformed. Consists of specific local named granitoids suite of I/S and some very small A type bodies.

The most distinguished, largest is I-type body "Sihla", although an I-types form a relatively minority part of Variscan granitoids (e.g. Broska-Petrík, 1993; Petřík-Kohút-Broska, 2001).

The Sihla tonalite to granodiorite massif is situated on the North side of main Alpine fault, the Muráň fault. According to Hraško *et al.* (2005) small magmatic more basic, tonalitic body, called "Málinec" tonalite, is observed on the South side of the Muráň fault.

Our study of zircons spots LA ICP-MS data from Málinec tonalite body reach Mississippian average ages, between 354,0 to 362,9 Ma.

This finding corresponds with precise *in-situ* U-Pb SHRIMP/SIMS zircon data from the Sihla I-type granitoids and refer about origin/emplacing during Late Devonian/Early Carboniferous (Mississippian) -349,9 ± 4,4 Ma to 357 ± 2 Ma (Siman & Čech, 2012, Broska *et al.*, 2013).

Tectonometamorphic Variscan evolution of the Western Carpathians can be compatible with a sinistral transposition

of a typical continental margin in main Variscan domains within Europe (e.g. Faure, 1998, Ledru *et al.*, 1999) and is linked with Meso-Variscan stage with middle crustal overthrusting/overheating and partial melting.

We are able to observe two stage of main Variscan melting in our previous SHRIMP/CHIME (zircon/monazite) study from orthogneiss; older, from 381,6 ± 6 Ma typically to 352 ± 4 Ma and younger 326 ± 10 Ma to 319 ± 4 Ma, which is probably connecting with extensional collapse of the thickened Variscan crust (e.g. Siman & Putiš, 2011, Putiš *et al.*, 2008).

The newest Late Devonian to Mississippian ages confirm and can be interpreted as continuing evolution of active Gondwana continental margin and arc related northward drifting microcontinental plate derived from Avalonian/Galatian superterrane (e.g. Putiš *et al.*, 2009, Stampfli, 2012).

The Alpine overprint reactivated existing of Variscan framework. The state of crustal unroofing after the Late Jurassic/Early Cretaceous compression was favorable for another deep crustal zones melting. The initial ⁸⁷Sr/⁸⁶Sr ratio 0,704655 of I- type Málinec tonalite was determined by TIMS apatite analyses. Although age calculations of biotite was highly enriched in radiogenic ⁸⁷Sr are not sensitive to the initial ⁸⁷Sr/⁸⁶Sr ratio, biotite with ⁸⁷Sr/⁸⁶Sr = 0,768391 yielded surprisingly 116 ± 5 Ma.

This Lower Cretaceous age probably represents the age of the last thermal event when the tonalite was heated above the closure temperature of Rb/Sr system of biotite and clearly allocate important role of thermal and tectonically basement reworking into the Alpine structures (Siman & Čech, 2012)

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Fry and Rf/Φ strain methods constraints and fold transection mechanisms; an example of progressive deformation in the Iberian variscides

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DIAS R.^{1,2}

Apúlia is a small Portuguese sector in NW of Central-Iberian Zone, that have been deformed in a non-coaxial sinistral transpressive regime during the first and main Variscan event (D1). This deformation give rise to a major NW-SE anticline, where the S1 N-S cleavage transect the inverted short NE limb; two and three-dimensional strain analysis have been done in the Ordovician quartzites of this limb using Fry and Rf/Φ methods on quartz grains.

The obtained Fry values are always higher than the Rf/Φ ones. The very low values of the D parameter estimated in Apúlia using Rf/Φ method ($0.03 < DRf/\Phi < 0.20$) and the higher values obtained for the same samples using the Fry method ($0.17 < DFry < 0.51$) show the predominance of intergranular processes over intragranular ones. Such conclusion is supported by microstructural studies of Central-Iberian quartzitic rocks (Mateus *et al.*, 2001). The incipient deformation expressed by the distortion of the quartz grains is also compatible with the weak development of S1 cleavage in the Apúlia quartzites. The stronger deformation related with the intergranular mechanisms shows that they have controlled most of the Variscan deformation in this region. The finite strain date coupled with geometrical and kinematical one and regional studies emphasize a polyphased structural evolution.

The shortening related to the Variscan precocce deformation give rise to a very open major anticline mostly by intergranular deformation mechanisms. At that time the regional D1 sinistral shear component (Ribeiro *et al.*, 1990; Dias *et al.*, 2013) was probably already active, being predominant along major shear zones. The progression of this regional sinistral transpressive deformation led to the tightening of the Apúlia anticline, which began to develop a NE facing. When the short limb attains a subvertical dip it becomes very efficient in concentrating the regional strike-slip component. Due to lithological heterogeneities (e.g.

matrix contend and layer thickness) the deformation is highly partitioned in Apúlia Ordovician sequence. Although the intracrystalline mechanisms are still important, the shape distortion of the quartz grains began inducing the S1 cleavage. This delay between the beginning of fold development and the related cleavage in Apúlia, coupled with the non-coaxial regional regime, explain the transection of folds.

The late stages of the D1 Variscan deformation in Apúlia, which led to the inversion of the NE short limb, should have been accomplished by both intergranular and intragranular deformation mechanisms.

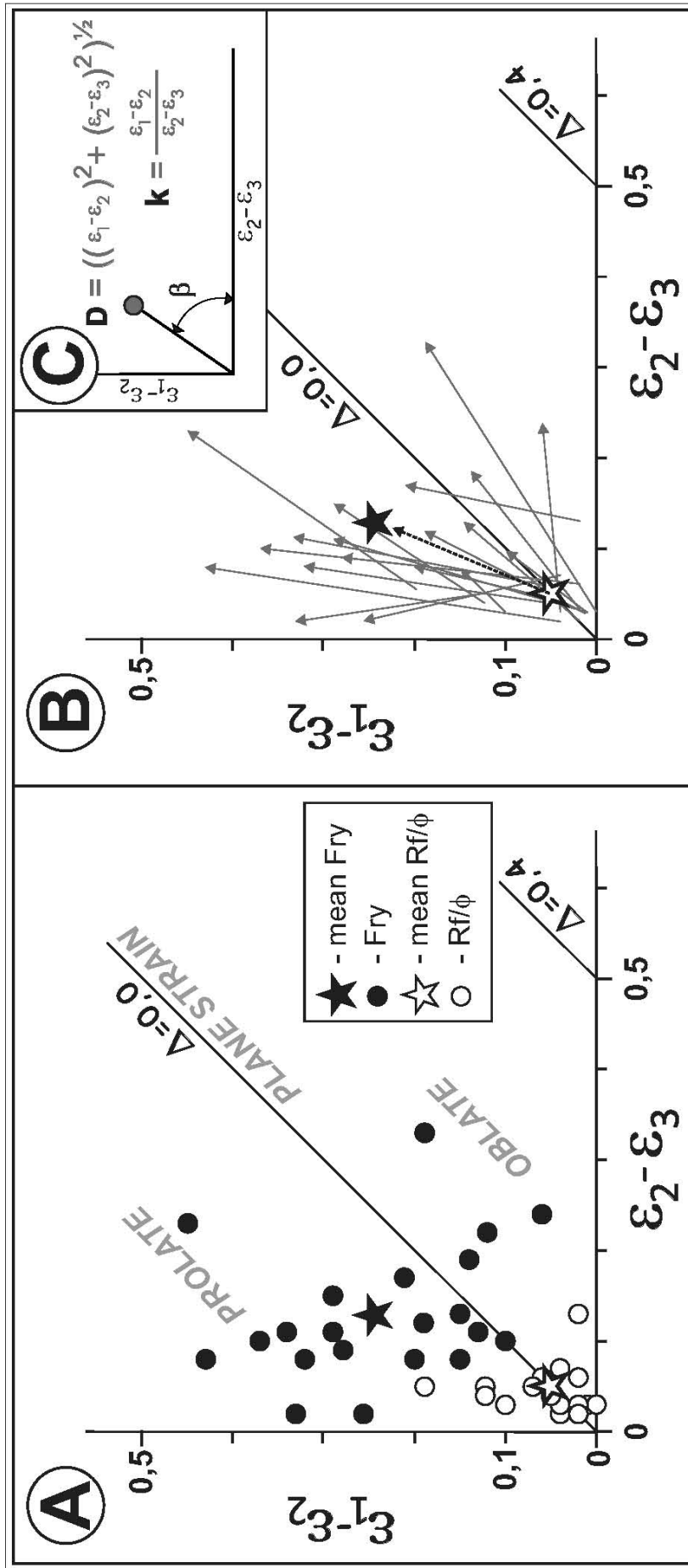
Concerning the strain ellipsoid shapes, the difference between the predominance of prolate ellipsoids estimated by Fry method (mean ellipsoid with a k value of 1.81 and a 61° β parameter) and the plane strain ones related to the Rf/Φ method (mean ellipsoid with a k value of 0.93 and a 43° β parameter) should reflect the more complex deformation evolution recorded by the intergranular deformation mechanisms in Apúlia. This constrictional strain fabrics are characteristic of the sinistral transpressive regimes dominant in the northern Central-Iberian Zone (Dias *et al.*, 2013).

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B) trend connecting the Rf/φ strain ellipsoid with the coeval Fry one (the stars represent the mean strain ellipsoids for both methods); C) strain ellipsoid parameters used in this work.

A) finite strain ellipsoids using both Normalized Fry and Rf/φ methods in the same quartzitic samples; both methods).

Crustal-scale 3D modelling of the Allochthonous Domain of the Saxo-Thuringian Zone: constraints from high-resolution 2D seismic profiles

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The various allochthonous units of the Saxo-Thuringian Zone displays the Variscan evolution between 400-300 Ma characterized by multiple subduction, exhumation and continental collision processes. During the late Carboniferous, the Saxo-Thuringian Zone was intruded by several granitic rocks. Subsequent reactivations of initially Variscan structures complete the complexity of the crystalline basement of the Erzgebirge, Vogtland and Fichtelgebirge (NW-Bohemian Massif). Despite extensive reflection and refraction seismic investigations, the architecture of the metamorphic assemblage until the upper mantle remains controversial because existing seismic reflection data could only unravel the upper 10-15 km of the crust.

We present a crustal-scale 3D model of the southern part of the Saxo-Thuringian Zone containing the seismic DEKORP profiles of MVE90, FB01-EV0 and GRANU95. To highlight lower crustal structures, the seismic data sets of the profiles were re-processed by Kirchhoff prestack depth migration. Geophysically, the model is further constrained by gravimetric and magnetic anomalies and the recent earthquake distribution. The uppermost part of the 3D model displays the first order tectonic units utilizing the extensive geological datasets of the region including 2658 drillings.

The shallow dipping metamorphic units in the upper crust are ruptured by two types of faults: (i) upper-crustal, listric NE-dipping faults (e.g. Gera-Jáchymov Zone, Flöha Zone, Elbe Zone, Lausitz Thrust) and (ii) crustal-scale faults (e.g. the listric Franconian Line, seismically active, steeply dipping Mariánské Lázně Fault). A NE striking, steep zone of weak reflectivity until the upper mantle constitutes the

early-Variscan strike-slip fault and boundary between the high-grade Allochthonous Domain and the low-grade Wrench-and-Thrust Zone (sensu Kroner *et al.*, 2007). We show that UHT-granulitic rocks overthrust the Wrench-and-Thrust Zone between low-angle detachment faults and crop out north of the Erzgebirge crystalline complex, *i.e.* the Saxon Granulite Massif. The geochemically distinct granites of the Erzgebirge (Förster *et al.*, 1999) form isolated granitic bodies and were emplaced along major tectonic structures. According to our seismic imaging results, most of the granites terminate at a depth of 5-10 km suggesting a laccolithic structure. This contradicts the classical view of a giant, deep seated Erzgebirge-Vogtland batholith (Tischendorf *et al.*, 1965). The transition to the mantle is represented by a laminated mafic lower crust at 27-30 km depth. Our 3D model is not in conflict with existing geophysical modelling (e.g. Enderle *et al.*, 1998; Hofmann *et al.*, 2000).

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Mantle-crust interaction recorded in the latest Variscan plutons of the Romanian Southern Carpathians

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The issue of granite petrogenesis plays a key role in the overall understanding of the growth and differentiation of continental crust, as well as in our ability to unravel the tectonic histories of orogenic belts. The petrogenesis and emplacement of granites in post-collisional tectonic settings is one of the thornier challenges, as these rocks are likely derived via thermal and magmatic processes within highly deformed and compositionally heterogeneous continental crust for which we still lack a clear understanding. Models for granite genesis away from plate margins have been successfully applied in comparatively young orogenic regions, such as the Himalayas, the Carpathians, and Turkey (e.g., Western Anatolia, Eastern Pontides). These models have proven challenging to employ in older orogenic belts, given their sometimes intricate tectonic and metamorphic histories, and the loss of pertinent evidence due to the effects of post-emplacement tectonic reworking, and often extensive alteration and erosion.

A series of ancient but fresh, age-correlative granitic plutons are exposed in Alpine nappes of the Carpathians Mts. in SW Romania. These granites, all mapped as intruding the Neoproterozoic basement of the Danubian terrane, were emplaced during the post-collisional stages of the Pan-African and a younger, Variscan event. We present here new data for six plutons (Furcătura, Muntele Mic, Culmea Cernei, Ogradena, Cherbelezu, and Sfârdinu) all post-dating the peak metamorphism associated with the Variscan continental collision in Europe (emplacement age ranging between 327 and 287 Ma), and are remarkably heterogeneous. The samples range from granites *sensu stricto* (biotite- and muscovite-granites, and amphibole-biotite granites) to quartz monzonites and have mineral assemblages dominated by plagioclase (An₁₂₋₄₀), K-feldspar, quartz, biotite, muscovite, and occasional

amphiboles. The common accessory minerals are titanite, zircon, garnet, ilmenite and clinozoisite, while the presence of magmatic epidote is restricted to Furcătura pluton. Major elemental compositions of the samples indicate that the granitoids are metaluminous to strongly peraluminous (ASI between 0.77 and 1.61), mostly high-K calc-alkaline, with few samples having shoshonitic and calc-alkaline affinities. All samples have trace elemental ratios (*i.e.*, [La/Yb]_N, [Dy/Yb]_N, [Gd/Yb]_N) indicative of garnet, amphibole, and clinopyroxene fractionation. Their Eu/Eu* ratios are highly variable at inter-pluton scale and are directly correlated with Sr content. The Eu/Eu* values, coupled with petrological data and thermometry (Ti-in-zircon and Ti-in-quartz; 575 to 860 °C) allow us to estimate the depth of emplacement of the plutons, which varies from 20 km to > 40 km. Furthermore, stable (O - measured on quartz mineral separates) and radiogenic (Sr and Nd) isotopic data are consistent with protoliths sourced in supra-crustal environments and the upper mantle. Isotopic data (⁸⁷Sr/⁸⁶Sr_i of 0.70437 - 0.73212; εNd of 0.62 to -10.84; and δ¹⁸O of 5.51 to 13.82) suggest that after the cessation of the Variscan collisional event, mantle melts contributed directly to the formation of granites, very likely during delamination. The pronounced variation in petrological and chemical compositions of synchronous plutons suggests that delamination in the Danubian domain was not a single, large scale event that affected the entire crust, but rather a collection of disparate, spatially and chronologically limited events, that affected the Variscan crust during the latest stages of the orogeny. Furthermore, the presence of mantle-derived signatures in the Danubian Variscan plutons shows that juvenile continental crust can be formed in post-collisional settings, long after the cessation of subduction and the peak collisional events.

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Coeval eclogitization and migmatization during orogenic collapse (Montagne Noire dome)

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The Montagne Noire (MN) Axial Zone is a well-studied dome of the Variscan orogenic belt. Yet the position of this dome of high-grade rocks in the foreland of the Variscan belt has been puzzling, and the relative roles of contraction, extension, and wrench deformation in the evolution of the MN dome have remained controversial. We present new structural, petrologic, and geochronologic data, paired with numerical modeling results, that inform the processes of formation and exhumation of the MN dome rocks and potentially reconcile apparent paradoxes, including the formation of eclogite and migmatite at about the same time.

The dominant protolith of the Montagne Noire migmatite dome is Ordovician granitoid that developed as augen gneiss during Variscan deformation. Other rock units include metasedimentary and metavolcanic rocks (fine grained gneisses), with mafic/ultramafic pods and layers (some with eclogitic assemblages). These units are ductilely deformed in the dome and offer excellent structural markers. The internal structure of the Montagne Noire dome (Fig. 1) includes a largely diatexitic northern dome (Laouzas-Espinouse) that includes several granite bodies (Montalet, Vialais), and a southern dome that extends from the Nore dome in the W to the Caroux dome in the E.

The northern dome contains complexly folded layering/foliation with variable lineation trends; strain increases toward the northern contact of the dome (C-S mylonites). The southern dome displays broad zones of intense deformation (presence of melt) in which granite bodies (Anglès, Soulié) are elongated, foliation is steeply dipping, and lineation is nearly horizontal. Solid-state deformation is restricted to the periphery of the MN dome. The structural sequence involves horizontal layering that was folded by upright folds; this layering and folds were

severely overprinted by shallowly dipping, solid-state to mylonitic fabrics at both the W (top-to-W) and E (top-to-E) terminations of the dome.

New monazite U-Pb dating results suggest that the augen gneiss deformed around 315-305 Ma, with the last melt crystallized at 305-300 Ma. Fine grained gneisses continued to deform and recrystallize in narrow high strain zones until ~295 Ma. Among the recognized eclogite localities of the MN, the best preserved Terme de Fourcaric eclogite (near Anglès granite, Fig. 1) yields P-T conditions of 1.4 GPa at 725 °C, and a U-Pb zircon age of 315.3 ± 1.6 Ma. Garnet zoning and inclusion suites, together with the pattern of rare earth element abundances in dated zircons indicate that 315 Ma is the age of eclogitization and not hydrothermal zircon growth as previously suggested. Therefore, eclogitization was essentially coeval with the flow of partially molten crust during the formation and exhumation of the MN dome.

We propose that eclogitization took place at the orogen-foreland transition during redistribution of mass from the orogenic paleo-plateau toward the foreland (Fig. 2). The dynamics of a collapsing plateau involves crustal thinning and therefore motion of the plateau edge toward the foreland, creating compression-transpression. During collapse the low-viscosity crust deep beneath the plateau also flows laterally toward the foreland as well as vertically in domes. During initial collapse of the Variscan orogen, the MN region underwent thickening (and eclogitization) driven by plateau extension and flow of deep crust from the plateau to the foreland. Shortly after their formation, eclogite bodies were entrained in the partially molten crust and exhumed in the MN dome. This scenario explains eclogitization and migmatization in the same orogenic collapse setting.

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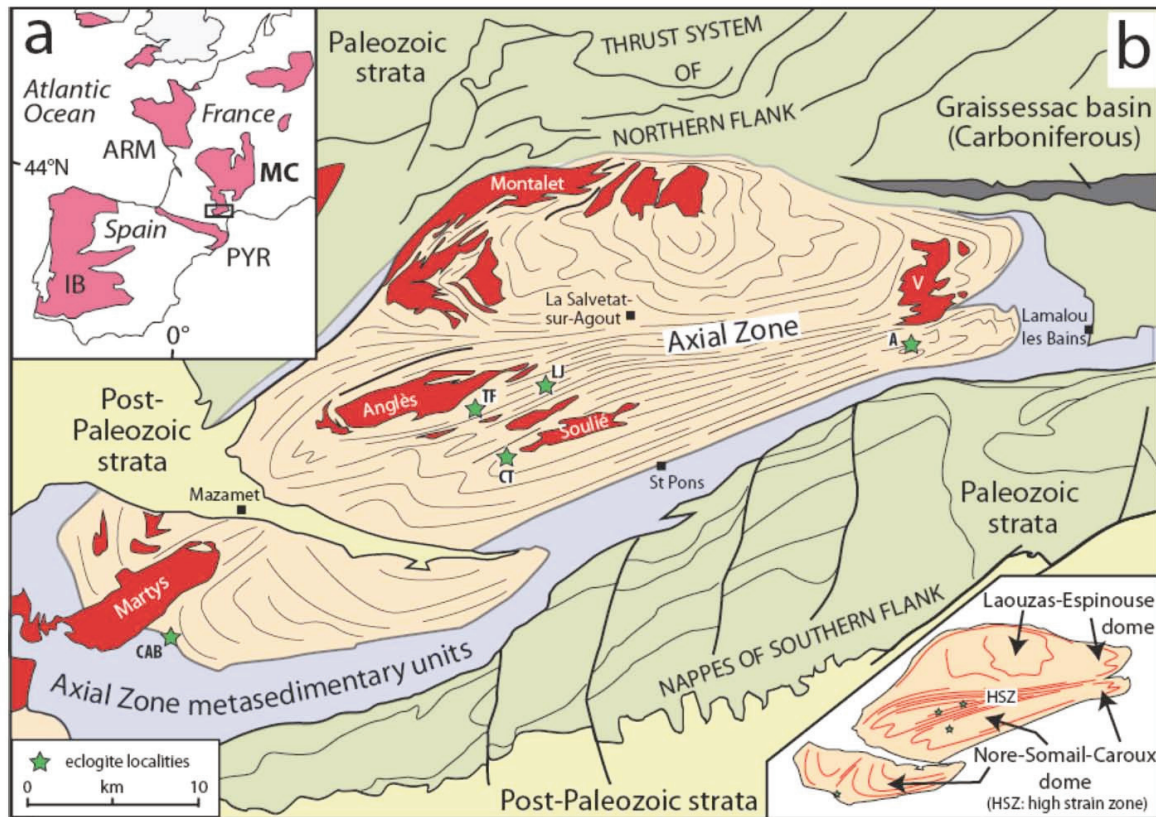


Fig. 1a.- Map of some of the Variscan massifs in western Europe: Armorican (ARM), Iberian (IB), the Massif Central (MC), and the Pyrenees (PYR). The rectangle at the southern end of the Massif Central shows the location of the Montagne Noire; (b) Simplified geologic map of the Montagne Noire (after Alabouvette et al., 1993, Carte 1:50'000 St Pons.; Demange et al., 1996, Carte 1:50'000 Lacaune); foliation trajectories after Rabin et al., 2015, *Tectonics*, in revision, and Roger et al., 2015, *Tectonophysics*, 640-641, 53-69, for the eastern end of the dome. The locations of eclogite are shown, and abbreviated as follows: A = Airette, CAB = Cabardès, CT = Cantausse, LJ = Le Jounié, TF = Terme de Fourcaric. Anatectic granites are labeled (V = Vialais).

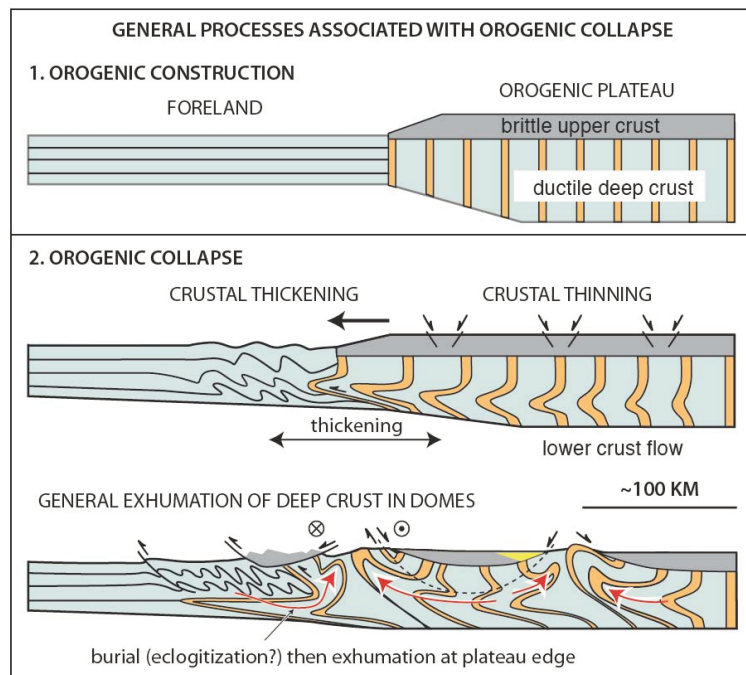


Fig. 2.- Conceptual model of the flow of partially molten crust laterally (in a deep crustal channel) and vertically (to form migmatite domes) at the transition between the thick crust of an orogenic plateau (including a ductile layer in the deep crust) and the thinner, cooler foreland during extension (figure based on 2D numerical models and modified from Rey et al., 2010, *Lithosphere*, 2, 328-332.).

High-Sr - Low-Yb (“adakitic”) Namuro-Westphalian peraluminous granites from South-Brittany: evidence for high-pressure crustal melting at the “collapse stage” of the Variscan orogen

THIÉBLEMONT Denis

For about twenty years, the systematic geological mapping (1/50 000) performed in the frame of the Carte géologique de la France program, in South-Brittany (about 12 new maps since 1999), has greatly increased the knowledge of Variscan granites; a voluminous (34 % of the surface), strongly significant and often neglected component of Paleozoic terranes in the South Armorican domain.

Abundant dating has been performed confirming that those granites mostly emplaced between c. 325 and 300 Ma, synchronously with the supposed “collapse stage” of the Variscan orogen. From the metamorphic parageneses recorded in the surrounding rocks at the time of emplacement, the granitic plutons may be thought to have crystallized in the medium to upper part of the crust ($P < 6$ kb).

Classical granitoid nomenclatures designate these granites as peraluminous biotite-granites and leucogranites, and isotopic analyses indicate a probable metasedimentary origin (Bernard-Griffiths *et al.*, 1985). Furthermore, these rocks generally display strongly fractionated rare earth element patterns, with high Gd/Yb ratios indicative of garnet stability in their protolith.

Systematic geochemical investigations based on extensive field and petrographical surveys performed in the course of geological mapping reveal that a significant part of the south Armorican peraluminous granites display high Sr contents conferring them the High-Sr - Low-Yb signature

characteristic of adakitic rocks (Defant and Drummond, 1991) (table). Petrographical observation as well as the low CaO concentration of these granites show that this high-Sr content is not a consequence of plagioclase accumulation and is therefore a primary feature of the granitic magmas. Contamination of these crustally derived magmas by a hypothetical Sr-rich mantellic component is also precluded owing to their high initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratio. Such a characteristic also discards the possibility that these granites would result from the melting of an amphibole oversaturated hydrous mafic source (Barboni *et al.*, 2011). Thus, high Sr contents may be thought to result from a high solubility of Sr during melting suggesting that plagioclase was not stable in the residue. Therefore, the most likely hypothesis is that melting occurred under eclogitic conditions.

Detailed petrological modeling is presently in progress which shows that temperatures of at least 800 °C and pressures of more than 20 kb were necessary to produce the south Armorican “adakitic granites”.

Present-day studies in the axial zone of the Montagne noire (Teyssier *et al.*, this volume) show that crustal melting under eclogite facies conditions would have occurred as late as 315 Ma in the Variscan orogen. Indeed the adakitic granites from South-Brittany could have been produced from such deep-seated portions of the crust, but after the magmas were generated, they traveled some 30 to 40 km upstairs to reach the region where we see them today.

	High-Sr - Low-Yb granites from South-Brittany							
Massif	Ergué	Carnac		Ste-Anne d'Auray		Brech	Quiberon	Guidel
Sample	BMV201	JM755	JM748	BMV181	BMV197a	JM290B	JM-403-2	FB9101
SiO ₂ (%)	66,58	69,4	70,4	70,98	67,86	72,8	67,5	69,2
TiO ₂	0,62	0,56	0,34	0,4	0,49	0,21	0,56	0,49
Al ₂ O ₃	16,24	15,3	15,9	14,97	15,57	14,77	16,2	14,8
Fe ₂ O _{3t}	3,08	2,24	2,27	2,31	2,94	1,46	3,16	2,55
MnO	0,04	0,03	0,04	0,02	0,02	0,03	0,05	0,05
MgO	1,09	0,8	0,8	0,55	1,06	0,44	1,2	1
CaO	1,39	0,9	1,6	1,15	1,82	1,28	1,5	1,4
Na ₂ O	3,57	2,7	4,1	3,2	3,31	3,5	3,1	3,3
K ₂ O	3,6	5,98	3,44	4,97	5,63	4,69	5,09	5,34
P ₂ O ₅	0,29	0,34	0,14	0,27	0,45	0,14	0,31	0,33
Loi	2,96	1,56	0,96	0,77	0,91	0,66	1,1	0,7
A/CNK	1,32	1,22	1,19	1,17	1,05	1,12	1,21	1,07
Li (ppm)	na	62	65	na	na	44	97	73
Cs	14,19	na	na	2,87	6,2	na	na	na
Rb	231,1	278	133	228,9	252	172	234	274
Ba	896	1348	612	905	1496	600	1399	1440
Sr	452	638	460	438	524	179	733	506
Th	21,56	34,6	8,4	29,45	51,67	7,9	34,8	26,7
U	13,23	8,9	1,9	9,74	9,09	2,6	8,5	7,7
Ta	2,27	1	0,8	1,23	0,109	0,8	1	0,9
Nb	12,45	19	12	10,77	12,46	7,4	13,1	14,6
Hf	5,55	4,6	2,5	5,83	10,9	2,6	7,9	6,7
Zr	214	391	171	229	389	83	278	325
Y	8,26	8,2	6,1	9,06	17,4	3,7	15,2	10
V	na	33	31	na	na	18	49	21
Co	4,12	5	5	2,27	4,29	nd	7	6
Cr	10,9	25	21	10,2	25,8	19	49	36
Ni	2,93	nd	nd	6,74	16	nd	nd	17
La	69,05	92,9	24,9	72,33	110,4	15,5	97,6	70,9
Ce	142,1	180,7	50,2	142,9	221,5	32,9	186,8	137,5
Pr	15,52	18	5,3	15,08	23,28	3,7	20	15
Nd	55,69	66,1	20,7	51,76	82,72	13,4	69,1	54,4
Sm	7,81	9,1	3,8	7,3	12,25	2,5	10,1	8,3
Eu	1,34	1,5	0,9	1,18	1,91	0,7	1,6	1,9
Gd	4,75	5,4	2,7	4,54	8,02	1,6	6,2	5,5
Tb	0,58	1	0,8	0,58	1,05	0,2	0,8	0,6
Dy	2,54	2	1,4	2,36	4,45	0,9	3	2,3
Ho	0,31	0,3	0,2	0,28	0,62	0,1	0,4	0,4
Er	0,93	0,7	0,6	0,86	1,44	0,4	1	0,9
Tm	0,12	nd	nd	0,11	0,13	nd	0,1	0,1
Yb	0,66	0,5	0,5	0,54	0,78	0,3	0,8	0,6
Lu	0,12	nd	nd	0,09	0,12	nd	0,1	0,1
Sr/Y	54,7	77,8	75,4	48,3	30,1	48,4	48,2	50,6
(⁸⁷ Sr/ ⁸⁶ Sr) _i		0,70563	0,7059					
EpsNd(T)		-4,1	-5,2					

New UHP evidences from the inner part of the Variscan belt: geology of the Chavanon sequence, French Massif Central

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ROLIN Patrick¹, DUBOIS Michel³, GONCALVES Philippe¹

The Chavanon sequence, in the west-central part of French Massif Central is a classical, but poorly known, example of inverted metamorphism and nappe stacking from the inner part of the Variscan Belt. From the bottom to the top, the lithological succession is (1) micaschists of the amphibolite facies, that consist of quartz, muscovite, sillimanite, plagioclase and garnet with local biotite and tourmaline, with a very low angle northwards dip. This sequence is classically referred as the parautochthonous unit (2) biotite-sillimanite metatexites intercalated with scarce marble lenses, also known as the lower gneiss unit and finally (3) various types of diatexites, the uppermost one being characterized by cordierite/quartz nodules.

The recent finding of kyanite-bearing granulite boudins included within migmatites, as well as inclusions of metamorphic microdiamonds in garnets from the parautochthonous unit suggest that the Chavanon sequence has been affected by a generalized HP event prior to its present structuration.

The contacts between each unit appear to be progressive except for the diatexites which locally cross-cut the foliation and form typical zones of melt collection.

The succession of deformation can be summarized as follows:

- a D0 HP event poorly;
- a D1 event associated with anatexis and the development of a vertical foliation. Partial melting is restricted to the upper part of the sequence. Several geochronological estimations argue for a ca. 375 Ma age for this anatexis event;
- a D2 event, during which the D1 foliation is overprinted by a flat foliation and cross-cut by a diatexite dated at 349 ± 4 Ma;
- a D3 event, affecting the lowermost part of the sequence, that corresponds to the development of the right-lateral vertical ductile shear zone known as La Courtine shear zone. This shear zone affects both migmatites and micaschists; the age estimations argue for a contemporaneity of both vertical and horizontal movement.

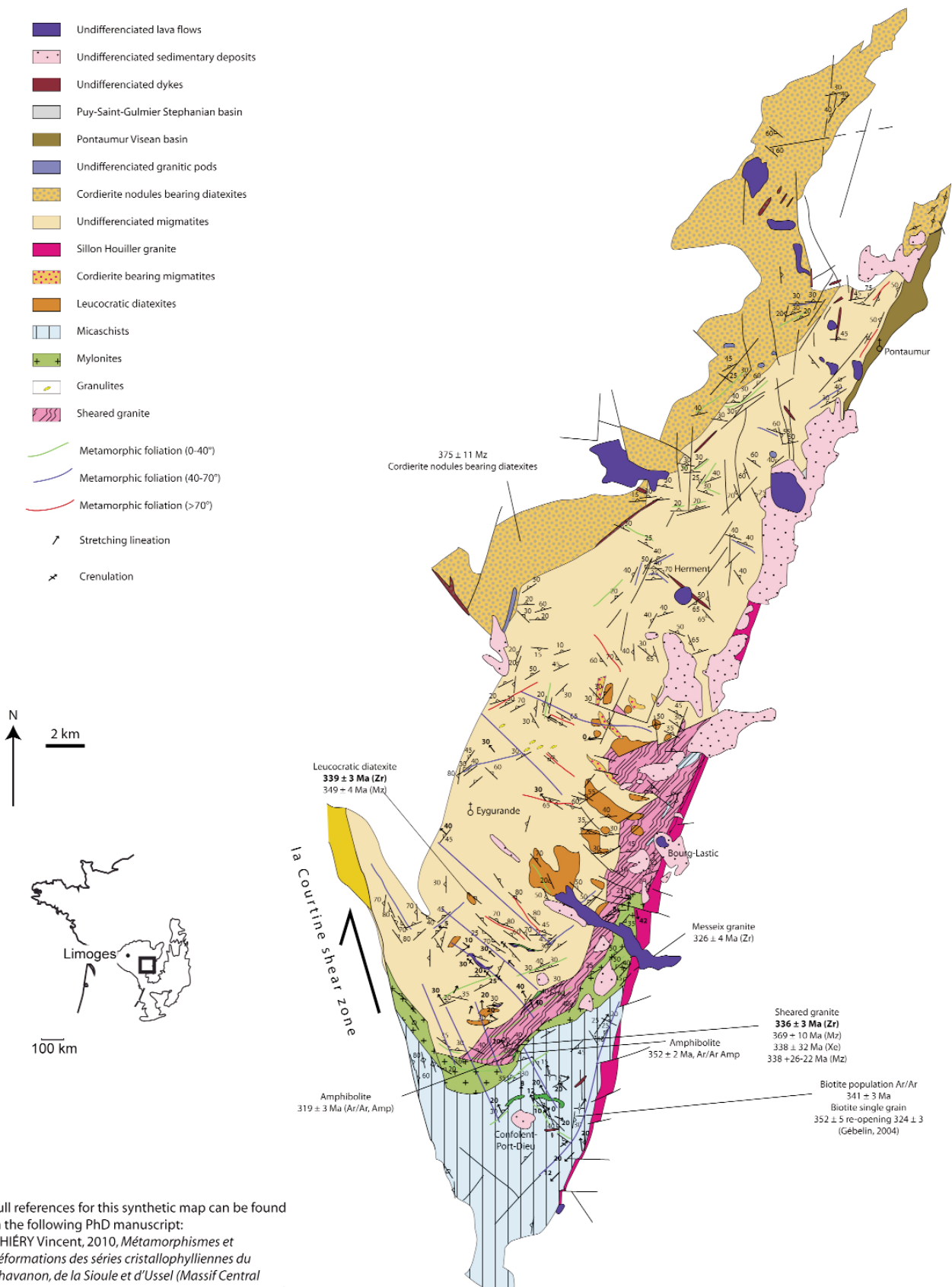
The succession of events from the whole lithological succession argues for a polyphase emplacement rather than a single nappe stacking; moreover, direct evidence of contact between units is lacking.

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Geological map of the Chavanon metamorphic sequence



Full references for this synthetic map can be found in the following PhD manuscript:
 THIÉRY Vincent, 2010, *Métamorphismes et déformations des séries cristallophylliennes du Chavanon, de la Sioule et d'Ussel (Massif Central français). Discussion du modèle de nappes du Massif Central*. Ph.D. Dissertation, Université de Franche-Comté [in French]. Besançon, France. 320 pp

Early to Late Carboniferous granitic and gabbroic intrusions in the eastern Pontides and their relations with the Variscan Orogeny in the Central Europe

TOPUZ Gültekin

The Variscan orogeny is considered to have formed by (i) the accretion of several Gondwana-derived terranes, Avalonia and Armorica, to Laurussia during the Late Ordovician and the Early Carboniferous, respectively and (ii) by subsequent collision of Gondwana with Laurussia at the northwestern end during the Late Carboniferous. This resulted in the formation of Pangaea during early Permian, and a westerly narrowing oceanic embayment, known as Paleo-Tethys. The eastern Mediterranean region (Greece, Turkey and Caucasus) is located at this westerly narrowing oceanic embayment of this orogene. Here we describe gabbroic and Early to Late Carboniferous high-K I-type granitic rocks from the pre-Permian basement of the Eastern Pontides, and discuss them within the Variscan orogenic framework.

The *Early to Late Carboniferous granitic rocks* occur at several localities (Gümüşhane, Köse, Olur, Yusufeli and Şiran), locally forming immense plutons (~600 km²). They are locally intrusive Early Carboniferous HT-LP metamorphic rocks. The Carboniferous granitoids are composite in nature, comprising high-K I-type granodiorite through granite to leucogranite. In general, the granitoids were variably affected by a later subgreenschist to greenschist-facies hydrothermal metamorphism, leading to partial to total resetting of the Ar-Ar systematics in biotite and hornblende. Timing of emplacement were best constrained by *in-situ* U-Pb zircon dating as 324 to 312 Ma. Samples of the granitoids display relatively enriched Sr-Nd isotopy with initial ⁸⁷Sr/⁸⁶Sr and ϵ_{Nd} values of 0.706-0.707 and -3 to -8, respectively. Overall, the geochemical features suggest a fractionation assemblage of plagioclase, hornblende and pyroxene without significant involvement

of garnet, and are consistent with partial melting of mafic lower crust.

The *Early Carboniferous mafic to ultramafic intrusions* occur as small stocks within the Early Carboniferous HT-LP metamorphic rocks in the Pülür area. Lithologically they are made up of a number of rock types, including plagioclase wherlite, melagabbro, and anorthosite with obvious cumulate texture, which are cut by dikes of ilmenite-bearing gabbro, leucogranite and late microdiorite. Cr-Al spinel, olivine and plagioclase were the first crystallizing phases, followed by pyroxenes and amphibole. This crystallization sequence and the compositions of plagioclase (An₉₅₋₈₄) and both pyroxenes (low Al₂O₃ contents) indicate crystallization from hydrous basaltic melts at relatively low pressures (0.2-0.5 GPa). Trace element abundances of early crystallized clinopyroxene in the amphibole-plagioclase wehrlites suggest that the parental magmas had fractionated REE patterns with (La/Yb)_{cn} ≈ 6.7. The LA-ICP-MS dating on zircons from the leucogranite dikes yielded a weighted age value of ~334 Ma. All the different rock types display similar initial Sr-Nd isotopic ratios (0.70732-0.70851 and ϵ_{Nd} = -4.1 to -7.2), totally identical with those of the Early to Late Carboniferous granites.

The Carboniferous metamorphic and igneous events in the Eastern Pontides and the Caucasus are probably related to the accretion to the Scythian Platform-Ukrainian shield in the north during the Early Carboniferous. However, it is unclear whether the southern margin of the Eastern Pontides was an active margin during the Carboniferous, or all the Carboniferous basic to acidic magmatism is related to the accretion to the northern continental domain.

Strain partitioning during migmatitic dome formation in the Variscan Montagne Noire massif (Southern French Massif Central)

TRAP P.^{1*}

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Significant crustal partial melting occurs during syn-orogenic thickening and the final stages of collisional orogeny in response to thermal relaxation and mantle to crust heat transfer. The deep partially molten orogenic crust is commonly exposed in migmatitic gneiss domes, which are defined by a granitic and migmatitic core mantled by a metamorphic envelop with high geothermal gradients. Large exposures of unmetamorphosed to weakly metamorphosed upper crust to migmatitic lower crust makes the Montagne Noire a valuable natural laboratory for studying the mechanisms responsible for crustal deformation and in particular the effect of partial melting on orogenic evolution. However, no consensus has yet been reached on the tectonic mechanisms responsible for the origin and the mechanical behavior of the Montagne Noire in this segment of the Variscan orogen. Here we present a precise structural analysis of the whole MNAZ accompanied by precise thermobarometric calculations on micaschists and garnet-cordierite-bearing migmatites located along a N-S trending profile. Particular attention has been paid to the structural setting of each studied sample in order to calculate P-T conditions with respect to deformation and to build P-T-D paths. New U-Pb LA-ICP-MS dating was performed on monazite grains from syntectonic granites, migmatitic gneisses and micaschists. The obtained ages lead to constrain in time the P-T-t-D evolution of the MNAZ.

The dome shape and finite strain pattern of the Montagne Noire Axial Zone (MNAZ) result from the superimposition of three deformations. The early flat lying S1 is folded by D2

upright ENE-WSW folds and transposed in the central and southern part of the MNAZ into steep D2 high strain zones consistent with D2 NW-SE horizontal shortening, in bulk contractional coaxial deformation regime that progressively evolved to non-coaxial dextral transpression. The D2 event occurred under metamorphic conditions that culminated at 0.6-0.8 GPa and 720 °C. Along the anatectic front S1 and S2 foliations are transposed into a flat lying S3 foliation with top-to-NE and top-to-SW shearing in the NE and SW dome terminations, respectively. These structures define a D3 transition zone related to vertical shortening during coaxial thinning with a preferential NE-SW to E-W directed stretching. Depending on structural level, the metamorphic conditions associated with S3 deformation range from partial melting conditions in the dome-core to subsolidus conditions above the D3 transition zone. We suggest that D2 and D3 deformation events were active at the same time and resulted from strain partitioning on both sides of the anatectic front that may correspond to a major rheological boundary in the crust. Above the D3 high strain zone, the metasedimentary cover records geothermal gradients of 20 to 50 °C/km. The end of D1 deformation was coeval with the onset of partial melting that occurred ca. 315 Ma. D2 deformation last from 315 to 305 Ma. Rocks with D3 fabrics give ages around 307-300 Ma. These new results lead to a better understanding of how the Variscan partially-molten middle crust behaved during Late-Carboniferous time, and to a discussion on the role of the anatectic front as a main crustal-scale rheological transition within a mature orogenic crust.

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Contribution to the geological and metallogeneny study of Bakoudou golden ore deposits (Gabon)

WAFIK Amina¹

KALIDOU Traoré², NAZAIRE Nzaou Mabika ¹, ALI Saquaque³

Gabon is a country in central Africa who's the geological history is part of the spatial and temporal framework of Africa's geology. The grounds found on the entire territory of the country show great geological diversity which translates Archean to recent Cenozoic formations. It contains important natural resources such Bakoudou golden deposit, located in the south at the Chaillu Archean massive.

Bakoudou golden deposit, has been owned by MANAGEM group, since 2005-2006. It has been carried during several research works with different objectives. A petrographic (macroscopic and microscopic) and geochemical (ICP-MS, XRD) studies of samples from two core holes (BA06-36: 13 samples and BH2: 1 sample), of Bakoudou gold deposit has been carried out. This work concerns the characterization. Several conclusions can be outlined:

- the chemical analysis of samples of the host rock of the mineralization in the southern extension gives SiO₂ contents ranging from 52.16 % (E3) to 74.87 % (E13). Based on silica contents, we can say that the rock is composed of intermediate to acids rocks (mesocratic to leucocratic). Thus, taking into account the mineralogical composition of our samples and the contribution of relatively low hydrothermal alteration, the primary paragenesis would probably be granitic to quartz diorite

and granodiorite;

- the appearance of recrystallized quartz crystals appearing as foliation in some rocks and the beginning of metamorphic banding, prove that these rocks have undergone regional metamorphism. In addition, the development of chlorite and sericite in some samples, is characteristic of hydrothermal alteration of low intensity;

- the X-ray diffraction spectra revealed particularly the presence of crossite in E5 and E8 samples. It is a sodium amphibole mineral tracer of the blueschist regional metamorphic;

- the metallogenic study reveals that gold which is our main interest is present as free grains disseminated in magmatic quartz, plagioclase, biotite and amphibole and particularly abundant in quartz. This corroborate with a primary magmatic origin of the gold. This does not exclude the contribution of hydrothermal fluid circulation, because it is highlighted in some laminations, where gold is associated with hydrothermal chlorite. Sulfides contained in the laminations are small amounts. A part of these is connected to a magmatic source and a greater quantity is related to a hydrothermal origin.

Keywords

Gold, Bakoudou, Gabon, Petrology, Geochemistry.

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Progress and pitfalls in linking age to stage in metamorphic rocks

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The rates and timescales over which mountain belts form during plate collisions provides constraints on the mechanisms by which continental crust is buried, transformed, deformed and recycled. Measuring the age of different geochronometer minerals precisely and accurately is now routine, but our understanding of how to link 'age' to 'stage' is lagging behind the analytical advances. In-situ laser ablation U-Pb and Ar/Ar datasets commonly yield a protracted range of dates rather than a single age, suggesting protracted crystallization over a range of PT conditions, inefficient resetting during cooling and exhumation or analytical mixing of growth zones. The interpretation of the dispersed ages hinges on additional chemical and/or textural data that tie the evolution of the

geochronometer phases to the pressure-temperature-deformation evolution of the rest of the rock. Trace element 'fingerprints' locked into co-crystallising phases such as garnet provide information about the crystallisation and dissolution history of U-Pb geochronometers during the prograde to peak part of the metamorphic cycle. Different Ar/Ar datasets together provide insight into the efficiency of Ar recycling during the retrograde part of the cycle, thus improving the interpretation of Ar/Ar ages with regards to the cooling/deformation/fluid history. Together these new 'petrochronology' tools provide a better key to unlocking how time is stored in metamorphic rocks during complex burial and exhumation histories.

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Tectonometamorphic evolution of the intracontinental orogeny exemplified by the Rehamna massif (Morocco, Variscan belt)

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Petrological observations, thermodynamic modelling and U/Pb in situ monazite dating have been used to provide new insights into the tectonometamorphic evolution of the Variscan Rehamna massif in central Morocco. This Palaeozoic metamorphic massif is located far from the Paleozoic convergent plate boundaries and represents a specific example of intracontinental orogen. Here, Late Proterozoic and Paleozoic sequences are affected by three main deformation events of variable intensity and geometry, associated with Barrovian and HT/LP metamorphism. The structural sequence is characterized by a flat-lying metamorphic foliation S1, deformed by WSW–ENE trending F2 folds with associated sub-vertical S2 cleavage, then heterogeneously reworked by NNE–SSW trending F3 folds with an S3 cleavage moderately to steeply dipping to ESE. Each deformation lead to the development of a new foliation and the crystallisation-deformation relationships show that biotite, chlorite, garnet, chloritoid and staurolite grew in the S1 fabric, and that chloritoid and staurolite continued their growth in the S2 and S3 fabrics. Two types of andalusite porphyroblasts located around granitic intrusions were identified: some are clearly post-tectonic whereas others are presumably coming from an early event. Based on the resulting P-T-d paths the following scenario is proposed: 1) Southward thrusting of Ordovician sequence over the Proterozoic

basement, its Cambrian sedimentary cover and the overlying Devonian-Carboniferous basin results to moderate thickening of thermally softened crust and burial metamorphism reaches peak of around 5.5 kbar and 575 °C. 2) Continuous shortening related to S2 fabrics results in minor burial followed by syn-convergent exhumation of deeply buried rocks (~5 kbar and ~580 °C). 3) S3 fabric is characterized by final exhumation of crust, reaching re-equilibration conditions at ~3 kbar, ~525 °C, associated with heating pulse related to late-tectonic voluminous magmatism marked by isobaric heating at ~3 kbar, locally reaching temperatures of ~550 °C. In situ U/Pb dating of matrix monazite allows dating of individual phases of metamorphism and constrain the duration of complex tectonometamorphic evolution outlined above. The geochronology results show two distinct age populations interpreted as dating 1) prograde Barrovian metamorphism at around ~300 Ma and 2) late metamorphic thermal overprint at ~276 Ma related to late D3 granitic intrusions. We suggest that the Rehamna massif represents a specific example of intracontinental orogen with a heat budget not related to convergent boundaries and we discuss potential heat sources and geodynamic setting of this metamorphic event in the frame of north Gondwana Variscan-Alleghanian evolution.

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Extrusion of anatectic lower crust from orogenic infrastructure: an example from the Eger crystalline unit (Bohemian Massif, Czech Republic)

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The Eger crystalline unit (ECU) represents a rapidly (1.1–2.5 mm/year) exhumed lower felsic crust that extruded along the Teplá-Barrandian – Saxothuringian suture zone at ~340 Ma. The ECU consists of high-grade gneisses and migmatites, granites, granulites and metasediments. Peak metamorphic conditions were established at ca. 740–845 °C and 14–16 kbar.

Detailed structural analysis of the ECU revealed four deformation events related to lower crustal flow and subsequent exhumation of the entire unit to middle crustal levels. The deformation record was studied along the profile following the Eger (Ohře) river. The oldest subhorizontally lying S_1 fabric is defined by monomineralic banding in migmatitic banded orthogneisses. This fabric is overprinted by sub-vertical, east-west trending axial planes and axial-planar cleavage S_2 with subhorizontal axes and typically shows strong deformation gradients, locally

forming mylonitic migmatites. These S_2 fabric related deformation gradients are associated with distinct lineation of variable plunge. Thus while in the S_2 low strain domains the lineation resulted from S_2/S_1 intersection and is subhorizontal, in the S_2 high strain domains the lineation reflects stretching and is subvertical. S_2 fabrics in the western part of the area are overprinted by open folds with NW-SE trending vertical axial planes (S_3) and subvertical axes. In the eastern part of the area, brittle-ductile kink bands with shallowly dipping axial planes affect the sub-vertical S_2 fabric. Locally, the S_2 fabric was exploited by pervasive porous waves of granitic melt that progressively transformed the banded orthogneiss to migmatitic gneiss and migmatites. Petrological observations suggest that such pervasive flow and emplacement of the granite sheets took place at relatively high pressures (>15–20 kbar at ~800–850 °C). Extensive melting of the gneiss was likely triggered by water/fluid influx.

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Pre-Alpine contrasting tectono-metamorphic evolution within the Southern Steep Belt (Central Alps)

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In the Southern Steep Belt, Italian Central Alps, relicts of the pre-Alpine continental crust are preserved. Between Valtellina and Val Camonica a polymetamorphic rock association occurs, belonging to the Upper Austroalpine units, which includes lithotypes from the Languard - Campo nappe (LCN) and the Tonale Series (TS).

Rocks belonging to LCN and TS are low to medium grade muscovite-, biotite- and minor staurolite-bearing gneisses and micaschists with interlayered garnet- and biotite-bearing amphibolites, marbles, quartzites and pegmatites, sillimanite-bearing gneisses and micaschists. Post-

Variscan (Permian) intrusives (granitoids, diorites and minor gabbros) occur.

The tectono-metamorphic evolutions reconstructed for these rock associations, permit the distinction of two contrasting tectono-metamorphic units (UTM), pre-dating Permian intrusives.

In this contribution we will discuss the geodynamic significance of these UTMs in the framework of the Variscan-Permian collision to extensional setting.

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Metagreywacke gneiss terranes rich in peraluminous granitoids - indications for a unique type of early Paleozoic orogeny

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In the Alps the pre-Variscan basement is composed of moderately to steeply oriented metapelites and metagreywackes (partly migmatic) with intercalated amphibolites and sheets of mainly peraluminous metagranitoids. Such gneiss terranes are the result of an orogenic type, which was globally widespread in early Paleozoic times and caused the formation of several 100 km wide subduction-accretion complexes at the periphery of Gondwana.

The corresponding orogen is referred as Cenerian belt (Zurbruggen 2015). The term "Cenerian" derives from the Ceneri gneiss - a key lithology of the Southern Alps. It is an anatectically-derived peraluminous metagranitoid rich in metasedimentary inclusions. Ceneri gneiss-like lithologies are typical for early Paleozoic gneiss terranes in the Alps and they are characteristic for the Cenerian orogeny.

A precondition for the formation of wide subduction-accretion complexes is a large sediment flux over geologically long periods. In the early Paleozoic the necessary sediment supply derived from the network of Pan-African belts. The sediments were deposited along the periphery of Gondwana, where they became accreted in long-striking subduction zones.

As a result of the large sediment input, the trench retreated ocean-wards and the mantle-derived magmas intruded the accreted greywackes. This initiated large-scale anatexis. The basaltic magmas solidified at these temperatures and mixing with the anatectically derived magmas occurred to a limited degree, only. Thus, the magmatism changed from calc-alkaline (typical for a magmatic arc) to peraluminous (typical for early Paleozoic subduction-accretion complexes; see figure). Volume estimations of the Ordovician metagranitoids and metavolcanics in the Alps indicate that about the lower fifth of the accretionary complex largely melted and intruded higher levels.

Today, on the globe, there is very limited overlap of regions of high terrigenous sediment supply with subduction zones. Only in the Gulf of Alaska, this situation is given. Therefore, the recycling of eroding mountain belts by the formation of subduction-accretion complexes is also referred as Alaskan-type.

Subduction-accretion complexes do not form cordilleras of high altitudes. They reach thicknesses of c. 30 km which are directly isostatically stable. Therefore, no over-thickened crust forms and no late to post-orogenic exhumation of the deep crust occurs. The lack of exhumation leaves the high-grade rocks at mid-crustal levels until they become involved in the Variscan collision. This explains why isotopic dating of the Cenerian orogeny can be disturbed by Variscan events.

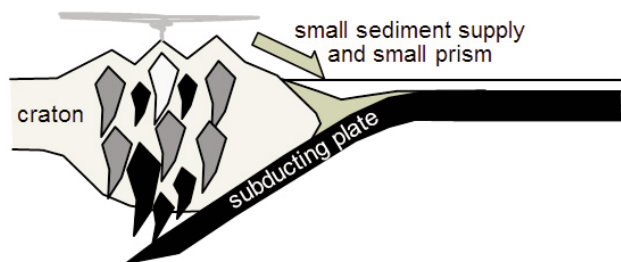
Conclusively, the early Paleozoic era was dominated by an orogenic style which was almost unique for its period. This is hitherto poorly recognized because large-scale anatexis and S-Type magmatism are often attributed to collisional or extensional plate tectonics. In addition, peraluminous metagranitoids of such gneiss terranes are widely interpreted by standard discrimination diagrams in their tectonic setting. This is a misleading practice, because peraluminous granitoids inherit their chemical and isotopic signatures from their greywacke source rocks, which themselves have inherited signatures from the hinterland they derived from.

The dynamics of subduction-accretion complexes which produced high amounts of peraluminous granitoids could explain the genesis of large parts of the mid and south European continental crust in early Paleozoic times.

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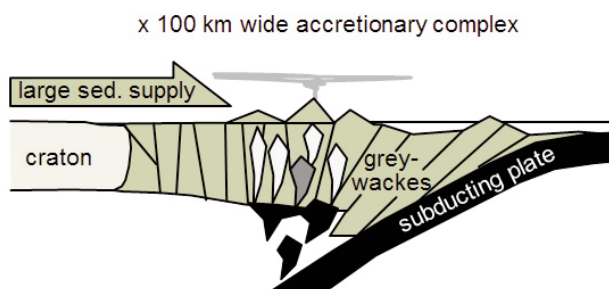
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Overthickened continental arc with calc-alkaline magmatism



Cadomian orogeny (Vendian-Cambrian) of the Andean-type

Subduction-accretion complex with peraluminous magmatism



Cenerian orogeny (Ordovician) of the Alaskan-type

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